NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3998

GROUND SIMULATOR STUDIES OF THE EFFECTS OF VALVE FRICTION, STICK FRICTION, FLEXIBILITY, AND BACKLASH ON POWER CONTROL SYSTEM QUALITY

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SUMMARY

Tests have been made on a power control system by means of a ground simulator to determine the effects of various combinations of valve friction and stick friction on the ability of the pilot to control the system. Various friction conditions were simulated with a rigid control system, a flexible system, and a rigid system having some backlash. For the tests, the period and damping of the simulated airplane were held constant.

The results show that, when valve friction was present in a rigid system, the introduction of stick friction was beneficial in that it restored some of the quality lost because of the valve friction. When flexibility was introduced between the pilot and the source of stick friction, stick friction was still beneficial but, with flexibility between the source of stick friction and the valve, no benefits were obtained from stick friction. When backlash was introduced between the pilot and the source of stick friction, the valve-friction effect was not so objectionable as in the rigid system; stick friction improved this system still further. With backlash between the stick and the valve (±0.025 inch at the valve), even the frictionless system was undesirable, and the addition of any combination of the frictions reduced the control quality still further.

INTRODUCTION

The ability of the pilot to control an airplane is dependent on a great number of control-system variables such as friction, backlash, and flexibility. Insofar as is known, no systematic study has been made to determine the effects of these variables. The National Advisory Committee for Aeronautics therefore has built a dynamic ground simulator for the purpose of such a study. In view of the large number of variables involved, it is doubtful that a precise definition of the optimum combination of these variables can be established; however, it is believed that the results will lead to a better understanding of each effect and may suggest some general design rules.

Previous investigations (for example, ref. 1) have shown that servocontrol-valve friction can reduce the quality of a power control system to such an extent that sensitivity problems and, in some cases, pilot-induced oscillations will result. It was suspected that the valve-friction effect is greatly dependent upon the mechanical characteristics of the linkages between the pilot and the valve such as static friction, flexibility, and backlash. Therefore, tests were made to study the effects of various ratios of valve friction to stick friction. The term "stick friction" is used hereinafter to denote the static friction in the mechanical parts of the system between the pilot and the valve. Various friction ratios were tested with a rigid control system, a flexible control system, and a rigid control system with backlash. For these tests the period and damping of the simulated airplane, the power-control time constant, the stick-force gradient, and the control-surface sensitivity were held constant. The results in this paper are therefore limited to the fixed values of these parameters.

SYMBOLS

t	time, sec
α	angle of attack, deg
δ	control-surface deflection, deg
$\dot{\gamma}$	rate of change of flight-path angle, deg/sec
θ	attitude angle, deg
ζ	damping ratio
ω_n	natural frequency, radians/sec
D	differential operator, d/dt
$\left(\frac{\alpha}{\delta}\right)_0$	steady-state ratio of α to δ

APPARATUS

Figure 1 shows a photograph of the simulator used in the tests and figure 2 presents a schematic drawing of the simulator. The simulator consisted of a chair that was designed to pitch in response to control deflection. The pitching motion, which is closely associated with the short-period mode of an airplane, is expressed by the following equation:

$$\text{Chair angle} = \theta = \frac{\alpha}{\delta}\,\delta + \frac{\alpha}{\delta}\,\frac{\dot{\gamma}}{\alpha}\int_0^t \delta\,dt \tag{1}$$

The term α/δ is the transfer function of a single-degree-of-freedom system with spring restraint and viscous damping. This transfer function may be written as follows:

$$\frac{\alpha}{\delta} = \left(\frac{\alpha}{\delta}\right)_0 \frac{\omega_n^{\,2}}{D^2 + 2\zeta\omega_n D + \omega_n^{\,2}} \tag{2}$$

This expression neglects the effects of tail lift on the acceleration at the center of gravity. The term $\dot{\gamma}/\alpha$ is the transfer function relating rate of change of flight-path angle to angle of attack. If the tail lift and unsteady lift effects are neglected, this term is a constant for any given flight condition.

A slide-valve-type power control unit typical of those used in present-day fighter airplanes was installed to act as the driving unit to pitch the chair. The piston rod of the actuator was attached to the chair and the end of the cylinder body was attached to a spring through a bellcrank. As can be seen from figure 2, extension or retraction of the actuator moved the bellcrank. This bellcrank can be considered to be representative of an airplane's longitudinal control surface. Motion of this bellcrank δ, when multiplied by the transfer function α/δ, supplies the first term in equation (1).

A cable was attached to the other end of the spring and passed around a pulley connected to the rigid support. This cable was geared to a hydraulic motor which was driven by a variable-displacement pump. The input arm of the variable-displacement pump was mechanically linked to the output of the power control actuator. This linkage determines the steady-state value of the product $\frac{\alpha}{\delta}\frac{\dot{\gamma}}{\alpha}$ in equation (1). Since no followup system was attached to the variable-displacement pump, motion of the power control actuator not only moved the "tail surface" and caused an initial change in angle of attack but signaled the variable-displacement pump to rotate the drum at a rate proportional to the displacement of the power control actuator. Thus, the variable-displacement pump produces the integration of δ shown in equation (1). Since the variable-displacement pump also moves the chair through the same spring to which the power actuator is connected, the transfer function α/δ also appears in the second term of equation (1). The overall effect of the variable-displacement pump can be considered to represent the pitching motion associated with curvature of the flight path resulting from lift on the wing. As shown in figure 2, a rotary-type damper was used to provide damping to the chair. The short-period dynamic characteristics are adjustable so that any flight condition of any airplane can be simulated. For these tests, the airplane dynamics were held constant. A time history of the response characteristics of the chair and also the simulated response of angle of attack following a step stick deflection are shown in figure 3.

A control stick was mounted to the movable frame through a ball bearing and was connected directly to the control valve of the power control unit by a push-pull rod. The mechanical advantage between the stick and the valve (that is, the ratio between linear motion of the stick grip and the valve motion, the output being fixed) was about 4:1. The inertia of the stick and the push-pull rod was about 0.22 slug-feet^2 and the stick length was about 24 inches. The ratio between stick rotation and rotation of the output bellcrank δ was 1:5. Here again all attachment points were made as frictionless as possible. As indicated in figure 2, an adjustable friction clamp was used to vary the stick friction. A similar arrangement was installed on the control-valve stem so that valve friction could be varied.

For these tests a simple cantilever spring attached to the stick was used to provide the pilot with feel forces. This spring supplied linear forces with stick deflection; these forces resulted in a feel gradient of approximately 4 pounds per inch of stick displacement. No preload was provided in the feel device. The chair when disturbed would return to within 0.1 degree of its trim position. This condition was caused by the summation of the small amounts of friction in the main support bearings, the pulley, and the chair damper. The stick grip could be moved approximately ± 0.02 inch without causing any motion of the power control actuator. This dead spot in the stick motion was caused primarily by the dead spot in the control valve. The lost motion between the stick and the valve was not perceptible to the pilot. The flow-stroke characteristics of the valve were nonlinear, small deflections providing relatively slower control-surface rates. However, the time constant of the servo response was very short compared with the response time of the simulator and was not considered to be a significant factor in these tests. The control valve itself had some inherent friction which amounted to about 4 ounces in terms of stick force. This valve friction was eliminated for the zero-valve-friction tests by means of a small vibrator mounted on the valve stem as described in reference 2.

It should also be pointed out that the power control unit used incorporated a viscous damper on the valve for the purpose of eliminating valve chatter. This damper was not changed throughout the tests.

The light bulb, lens, and mirror were attached to the chair and arranged so that a spot of light was projected on a screen located in front of the pilot. Motions of the light spot indicated to the pilot the attitude angle of the chair. A second spot of light was also projected on the screen and was controlled by a cam. The cam-driven light spot moved from one vertical position to another on the screen, and the pilot attempted to make the light spot for the chair coincide with the cam-driven light spot.

Strain gages were mounted on the control stick to measure control forces, and slide-wire transmitters were used to measure stick position, chair angle, and cam position. These four quantities and time were continuously recorded on standard NACA recording instruments during the tests.

TESTS AND PROCEDURE

For these tests the dynamics of the simulator were adjusted to correspond approximately to those of a fighter airplane flying at an altitude of 10,000 feet and Mach number of 0.80. The period was set to be 1.0 second and the damping ratio, 0.45. The simulator was adjusted so that the stick deflection per degree of stabilizer deflection was made larger than its normal value to represent the gearing that would be provided by use of a mechanical-advantage changer in the airplane. With this arrangement, the steady-state ratio of angle of attack to stick deflection was approximately 0.60. The variable-displacement pump was adjusted to provide a steady-state value of about 1 degree per second per degree for the ratio of pitching velocity to stick deflection.

The pilots' task during the tests involved keeping the light spot for the chair lined up horizontally with the cam-driven light spot. The ease and precision with which the pilots could follow the cam-driven light spot provided the basis for the judging of the quality of the control system. In addition to the recorded data, the pilots' opinions were weighted heavily when the various configurations were evaluated.

The friction conditions tested are shown in figure 4. All values of friction quoted in this paper are given in terms of stick force. These conditions were tested with a rigid control system, a flexible control system, and a rigid control system having some backlash.

For each test configuration, at least two NACA test pilots obtained data.

RESULTS AND DISCUSSION

Rigid Control System

Examples of the data obtained are shown as time histories in figure 5 for various representative friction conditions. The quality of each configuration is indicated by the overshoots and oscillations in the chair record and also by the length of time required to make the chair record coincident with the target record. Coincidence of the two records indicates that the pilot was "on target."

Figure 5(a) shows representative results obtained when the control system was essentially free of all friction. The absence of large overshoots and oscillations in addition to the relatively short length of time required to get on the target indicated that the pilot had little difficulty in performing the task. The pilots commented favorably on this system although they believed that the 1/2-pound limit of stick friction quoted in reference 1 would be necessary in flight. The small stick friction would be helpful in alleviating the small unintentional control inputs that may result from such things as the many duties of the pilot which momentarily divert his attention from the control of the airplane or rough-air conditions.

Some tests were made with the vibrator removed from the valve stem. Without the vibrator the valve friction was about 4 ounces in terms of stick force. The pilots could not detect any effect of this small amount of friction and the records were very nearly identical to those shown in figure 5(a). For this reason the tests with 4-ounce valve friction are not shown.

Figure 5(b) shows the effects of $1\frac{1}{2}$ pounds of friction in the control valve. The overshoots, oscillations, and the relatively long time required to get on the target are good indications of the amount of control system quality lost through the introduction of the valve friction. The latter portion of the record shows the extreme difficulties encountered in positioning the chair precisely on a given point. This effect has been measured in flight and is discussed in reference 1. During the simulator tests the pilots believed that $1\frac{1}{2}$ pounds of valve friction were objectionable. They did not object on the grounds of the resulting increase in forces nor did they believe the system to be subject to violent pilot-induced oscillations. The objections were based simply on their inability to make fine corrections precisely and their feeling that the machine was flying the pilot.

Figure 5(c) shows the results obtained when the $1\frac{1}{2}$ pounds of stick friction were used in conjunction with the $1\frac{1}{2}$ pounds of valve friction. Although the total breakout force at the stick due to friction was increased, the overall performance was improved; the stick friction also restored the pilot's feeling that he had control of the machine. The stick friction locked the valve push-pull rod and thereby allowed the followup to return the valve to neutral.

Figure 5(d) presents the results obtained with about $2\frac{1}{2}$ pounds of valve friction. The records show that control through such a system is rather hopeless. The tendency for the chair amplitude to increase is a good indication of the actual danger associated with this amount of valve friction. It should be remembered that the simulator does not include the effects of rough air or the acceleration effects on the pilot or parts of the system. These factors which are present in flight will aggravate the oscillatory nature of the system and therefore will magnify the danger involved. The pilots noted that, even though these aggravating factors were absent in the simulator, the slightest distraction could very easily lead to violent pilot-induced oscillations. It seems safe to say that violent oscillations could be caused in flight by valve-friction values less than the $2\frac{1}{2}$ pounds for the same flight conditions and stability parameters set up in the simulator.

Figure 5(e) shows the results when $2\frac{1}{2}$ pounds of stick friction were introduced in addition to the $2\frac{1}{2}$ pounds of valve friction. Even though the figure shows that the pilot could get on the target, the large overshoots suggest difficulties that make precise control somewhat uncertain. The stick friction, however, was noticeably beneficial since the violent oscillatory tendencies were eliminated. The pilots verified these observations but objected to the system not only on the basis of precise control but also because of the amount of work involved. All pilots agreed that a total breakout force due to friction of about 3 pounds or less would be more desirable in flight for airplanes of the type being simulated.

Some tests were also made in which the valve friction was reduced to zero by means of a small vibrator and various amounts of stick friction were evaluated. The pilots could do a much better job with the highest stick friction tested (3 pounds) than they could with only $1\frac{1}{2}$ pounds of valve friction. Actually, the best performance was achieved when the stick friction was in the range between 1/2 and 2 pounds and the pilots believed on the basis of these tests and on the basis of their previous experience that they would prefer such systems for actual flight.

Tests were also made in which the valve friction was held constant and the stick friction was varied. From these tests it was learned that, when valve friction was present, the best control quality was achieved when the stick friction was equal to or very slightly greater than the valve friction. An excess or deficiency in stick friction, however, resulted in some quality reduction; the system with more stick friction than valve friction was considered to be desirable provided that the total breakout force due to friction did not exceed 3 pounds.

The results thus far discussed have been condensed into a plot of stick friction against valve friction (fig. 6) which shows the good, tolerable, and unsatisfactory combinations of these two types of friction. It should be pointed out that the conditions rated unsatisfactory were, in general, flyable but would be very objectionable from a precision control standpoint and would be very tiring to the pilot over long periods of time. Even though the figure shows that good performance can be obtained with as much as 1 pound of valve friction and 1 pound of stick friction, the designer should strive to decrease the valve friction as much as possible. This decrease would result in a smaller total friction force and a better performing control system. This point is extremely difficult to show graphically and no attempt was made to do so in figure 6; however, it is worth mentioning because the tests indicated that, as the system approached the condition of pure stick friction, performance and pilot impression improved.

Another point that should be brought out is that figure 6 applies only to the conditions of the tests and would not be expected to apply if other devices such as valve centering springs were used to attempt to compensate for the valve friction.

Flexible Control System

Since this paper is concerned primarily with the effects of friction, the complete effects of flexibility are not treated here. Subsequent tests should be made to determine the effects of various combinations of flexibility and valve friction on control quality. Limited tests on flexibility are included in this paper to illustrate the effect that it produces when introduced in the presence of stick friction and valve friction.

The rigid push-pull rod connecting the stick to the control valve was modified to include a flexible link to simulate a flexible control system. This modification also placed the flexibility between the feel device and the valve. The spring constant of the flexible link was set to a low value (4 pounds of stick force per degree of stick angle) so that the effect would be easily recognized. The same type of tests and friction conditions as described in the previous section were evaluated and representative records of these tests are presented in figure 7.

Figure 7(a) shows the results with a frictionless system, and the similarity between figure 7(a) and figure 5(a) shows that the flexibility had little or no effect. The pilots agreed that the flexibility was not detectable in this condition and therefore they rated this system the same as the rigid system. Here again the system was tried with 4 ounces of valve friction. The pilots believed that the friction effect was a little more noticeable in the flexible system than in the rigid system but they still considered the configuration to be tolerable. The flexibility magnifies the undesirable valve friction effect by allowing the valve to "motor" the control surface through a certain range, dependent on the amount of valve friction, by deflecting the flexible link. Also, the forces which the pilot applies in attempting to compensate for the motoring must be transmitted to the valve through the flexible link. When valve friction is present, therefore, the valve will not move until the pilot's force has deflected the flexible link to the point at which the spring force in the link overcomes the valve friction.

Figure 7(b) shows the difficulties introduced by $1\frac{1}{2}$ pounds of valve friction in conjunction with the flexibility. Even though figure 7(b) does not differ much from figure 5(b), an overall comparison of all the records obtained showed that the flexibility caused a very definite reduction in control quality. The pilots remarked that pilot-induced oscillations were possible with this system; however, they felt that such oscillations could be controlled somewhat by intense concentration. The skill and experience of the pilots involved in these tests were believed to be important factors in the prevention of violent oscillations with this system.

Figure 7(c), which shows the results for $1\frac{1}{2}$ pounds of stick friction and $1\frac{1}{2}$ pounds of valve friction, proves that stick friction is not beneficial when flexibility exists between the stick and the control valve. In fact, the overall performance with this system seemed to be worse than that obtained with valve friction alone, and the pilots noted that the stick friction removed the small amount of control confidence that was present in the system with valve friction only. This result is understandable since the stick is no longer rigidly connected to the valve because of the flexible link; thus, the stick friction is prevented from "locking" the control push-pull rod and the valve is allowed to center itself. Stick friction in such a system only reduces the quality still further by causing a nonlinear relation between the stick force and stick motion. It is interesting to note that pilots having considerable experience in controlling systems involving valve friction alone can more or less cope with the difficulties and produce surprisingly good performance although they invariably comment that such systems are unsatisfactory. It is believed that these pilots are successful because they change their technique of flying, as explained in reference 1, from force consciousness to position consciousness because valve friction destroys the relationship between force application and control-surface position. This method of changing techniques is not successful, however, when flexibility is introduced in the presence of valve friction because the flexibility destroys the relationship between the stick position and the control-surface position.

Figure 7(d) presents the results obtained with $2\frac{1}{2}$ pounds of valve friction and figure 7(e) shows the results obtained with $2\frac{1}{2}$ pounds of stick friction and $2\frac{1}{2}$ pounds of valve friction. The performance of both systems appears to be similar in that precise control is impossible; the pilots remarked that both systems were extremely susceptible to violent oscillations and they could not detect any benefits from the stick friction.

Figure 8 shows the ranges of good, tolerable, and unsatisfactory combinations of stick friction and valve friction when flexibility exists between the stick and the valve. This figure applies only to cases in which the flexibility is the same as that quoted previously. No doubt the limits will change depending upon the amount of flexibility present; however, the figure shows the detrimental effect on control quality since with this amount of flexibility only 4 ounces of valve friction could be tolerated.

The control stick was modified to include a flexible link to simulate flexibility between the pilot and the point at which stick friction was applied. This modification also placed the flexibility between the pilot and the feel spring. The amount of flexibility in this system was the same as was introduced between the stick and valve. The stick was again connected to the control valve by means of a rigid push-pull rod.

Figure 9(a), which represents a frictionless system, shows no large differences from the rigid system of figure 5(a) and the pilots could not feel any effects of the flexibility.

Figure 9(b) presents the results with $1\frac{1}{2}$ pounds of valve friction. Comparison with figure 5(b) shows that a little less difficulty was encountered with this system than was experienced with the rigid system. The pilots' complaints, however, were very similar to those regarding the rigid system with $1\frac{1}{2}$ pounds of valve friction in that precise control was difficult but violent oscillations were not probable.

Figure 9(c) shows the results of $1\frac{1}{2}$ pounds of stick friction and $1\frac{1}{2}$ pounds of valve friction. This figure shows that, in spite of the increase in breakout force, the performance is very similar to that shown in figure 9(b). The pilots, however, stated that the stick friction was helpful in restoring their feeling of control and therefore they rated this system above the system represented by figure 9(b).

The effect of $2\frac{1}{2}$ pounds of valve friction, which is shown in figure 9(d), was to cause the system to be subject to violent oscillations and to make precise control impossible. Comparison of figure 9(d) with figure 5(d) shows that the valve-friction effect was, however, not so severe as that obtained with the original rigid control system. The addition of $2\frac{1}{2}$ pounds of stick friction, shown in figure 9(e), did not improve the precise control of the system. It did, however, restore the pilots' feelings of being able to prevent any violent oscillations.

No attempt was made to establish limits, as was done in figures 6 and 8, because, as mentioned previously, more detailed tests are needed to do so. Comparison of figures 7 and 9 does show, however, the importance of the location of the flexibility when valve friction is present. The pilots commented that flexibility between the pilot and the source of stick friction is far more tolerable from the pilots' standpoint than flexibility between the source of stick friction and the valve. In practice, this result means that stick friction can be beneficial even in a flexible system if the equivalent stick friction (friction between the valve stem and airplane structure) is introduced very close to the power control unit. Also, the feel device should be located between the source of flexibility and the valve.

Control System With Backlash

As in the case of the flexibility tests, the limited results regarding backlash are included in this paper to show the general effects of backlash when introduced between the control stick and the valve and also between the pilot and the source of stick friction. The points at which the backlash was introduced are shown in figure 2.

The push-pull rod connecting the stick to the valve was modified so that there was about ± 0.025 inch of backlash, in terms of valve motion, between the stick and the valve. This modification also placed the backlash between the feel device and the valve. This backlash amounted to about ± 0.10 inch of motion at the stick grip.

Figure 10 shows time histories of the effect of backlash between the stick and the valve for various friction conditions. These figures show that, even with a frictionless system, the pilots could not position the chair precisely and, as the breakout force was increased, the control quality deteriorated. The pilots noted that, even with the frictionless system, precise control was difficult and, as the valve friction was increased, the danger of oscillating became more pronounced. Stick friction also produced the same results but the pilots believed that the stick-friction effect was not so objectionable as the valve-friction effect. The important point is that none of the conditions were even tolerable with this amount of backlash at the valve.

The backlash between the stick and the valve was then removed and the same amount of backlash was introduced between the pilot and the point at which the stick friction was applied. This modification also placed the backlash between the pilot and the feel spring. The results from these tests are presented in figure 11. The frictionless system, as shown in figure 11(a), was not too difficult to control even though the pilots could feel the backlash in the stick. With $1\frac{1}{2}$ pounds of valve friction (fig. 11(b)), the system performance was very similar to, but possibly a little better than, the original rigid control system with the same friction condition. Precise control was difficult but the system showed no tendency to produce violent oscillations. It should be remembered that this same friction condition when coupled with backlash between the stick and the valve produced a very dangerous system that was susceptible to severe oscillations. With backlash between the pilot and the source of stick friction, the stick friction improved the system. (See fig. 11(c).) Even though the initial overshoot tended to be larger, the pilot could position the chair on the target. This improvement is in direct contrast to the detrimental effects of stick friction when the backlash was between the stick and valve. Figure 11(d) shows the results of $2\frac{1}{2}$ pounds of valve friction and figure 11(e) shows $2\frac{1}{2}$ pounds of valve friction and $2\frac{1}{2}$ pounds of stick friction. In each case the performance shows that no violent oscillations were ever encountered although precise control was extremely difficult. The pilots commented that with valve friction the system was subject only to mild oscillations and this tendency was completely removed by the addition of stick friction. These observations lead to the conclusion that the backlash between the pilot and source of stick friction is not nearly so dangerous as the backlash between the stick and the valve. In fact, the records and comments regarding the backlash between the pilot and stick friction indicate that valve friction was not so detrimental to this system as it was to the rigid control system with comparable friction conditions. It was noticed during the tests of the rigid system with valve friction alone that the pilots, when they wished to stop the chair motion, applied the necessary opposite force in a jerking manner that resulted in an instantaneous "kick" on the push-pull rod which centered the valve. It is possible that, with the backlash between the pilot and the source of stick friction, the stick acted as a convenient "hammer," within the backlash range, with which the pilots tapped the control rod to break the valve friction. More detailed tests are required, however, to establish a more definite explanation for the behavior of backlash in this particular location.

CONCLUSIONS

Tests have been made with a ground simulator incorporating a power control system. The purpose of the tests was to determine the effects of various combinations of valve friction and stick friction on the ability of the pilot to control the system. Various friction conditions were simulated with a rigid control system, a flexible system, and a rigid system having some backlash. From these tests the following conclusions can be drawn:

1. When valve friction is present in a rigid control system, stick friction is beneficial in restoring some of the quality lost because of the valve friction. The optimum quality is achieved when the stick friction is equal to or slightly greater than the valve friction measured at the stick.

2. The total breakout force due to friction should not exceed 3 pounds in terms of stick force. Control-system quality improves as the valve friction is reduced; however, reducing the valve friction below 4 ounces did not yield any significant improvement.

3. When flexibility existed between the valve and the source of stick friction, the undesirable effects of valve friction were magnified by the flexibility, and the introduction of stick friction reduced the quality still further.

4. When flexibility was introduced between the pilot and the source of stick friction, stick friction was again beneficial in restoring some quality lost because of the valve friction.

5. With backlash between the stick and valve (±0.025 inch at the valve), precise control was difficult even with the frictionless system, and the quality deteriorated as valve friction or stick friction was increased.

6. With backlash between the pilot and the source of stick friction, the valve-friction effect was not as objectionable as it was in the rigid

system, and the introduction of stick friction improved the system still further.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., February 8, 1957.

REFERENCES

1. Phillips, William H., Brown, B. Porter, and Matthews, James T., Jr.: Review and Investigation of Unsatisfactory Control Characteristics Involving Instability of Pilot-Airplane Combination and Methods for Predicting These Difficulties From Ground Tests. NACA RM L53F17a, 1953.

2. Phillips, William H.: Investigation of Effect of Reduction of Valve Friction in a Power Control System by Use of a Vibrator. NACA RM L55E18a, 1955.

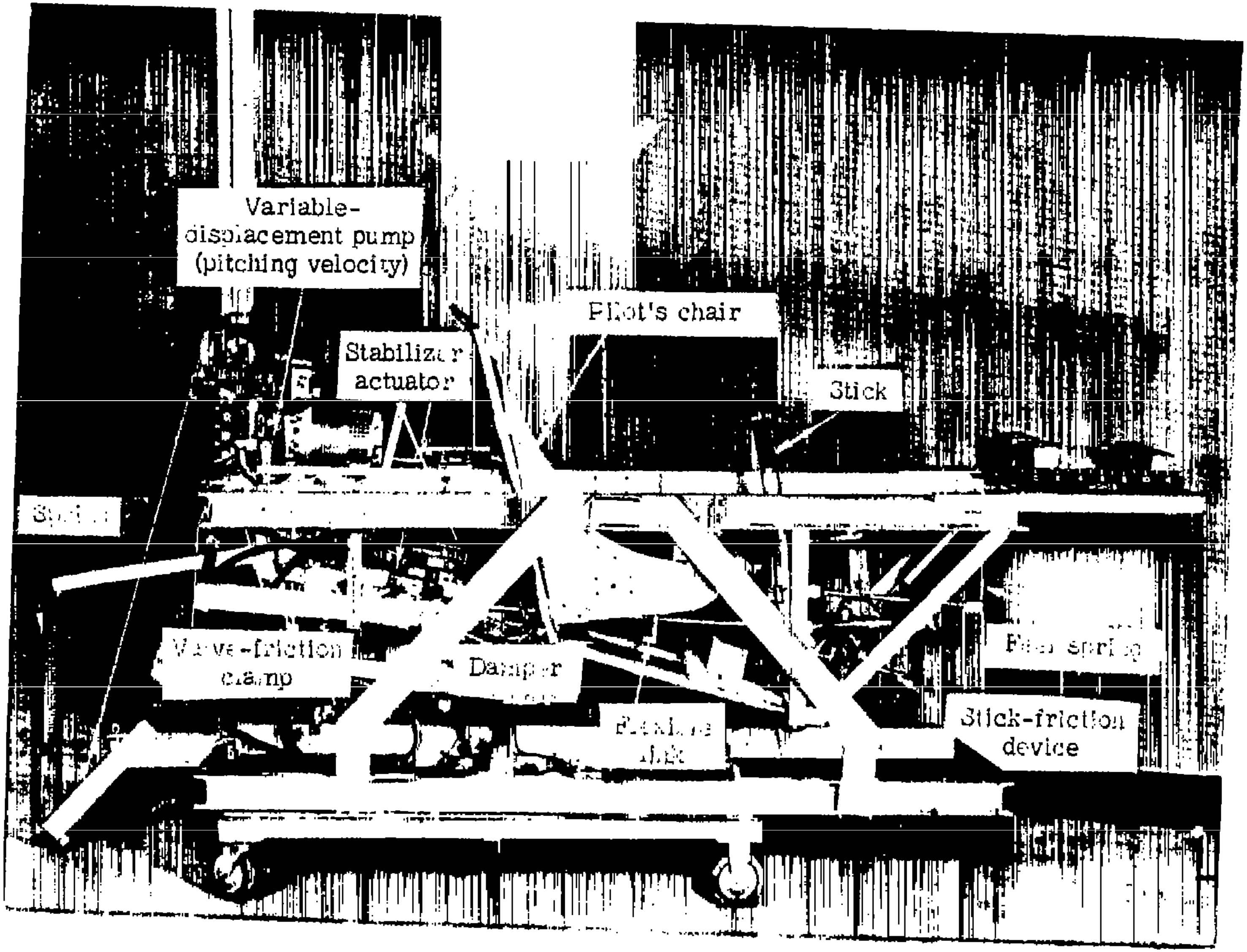


Figure 1.- Longitudinal power control simulator (Pitch chair). L-90186.1

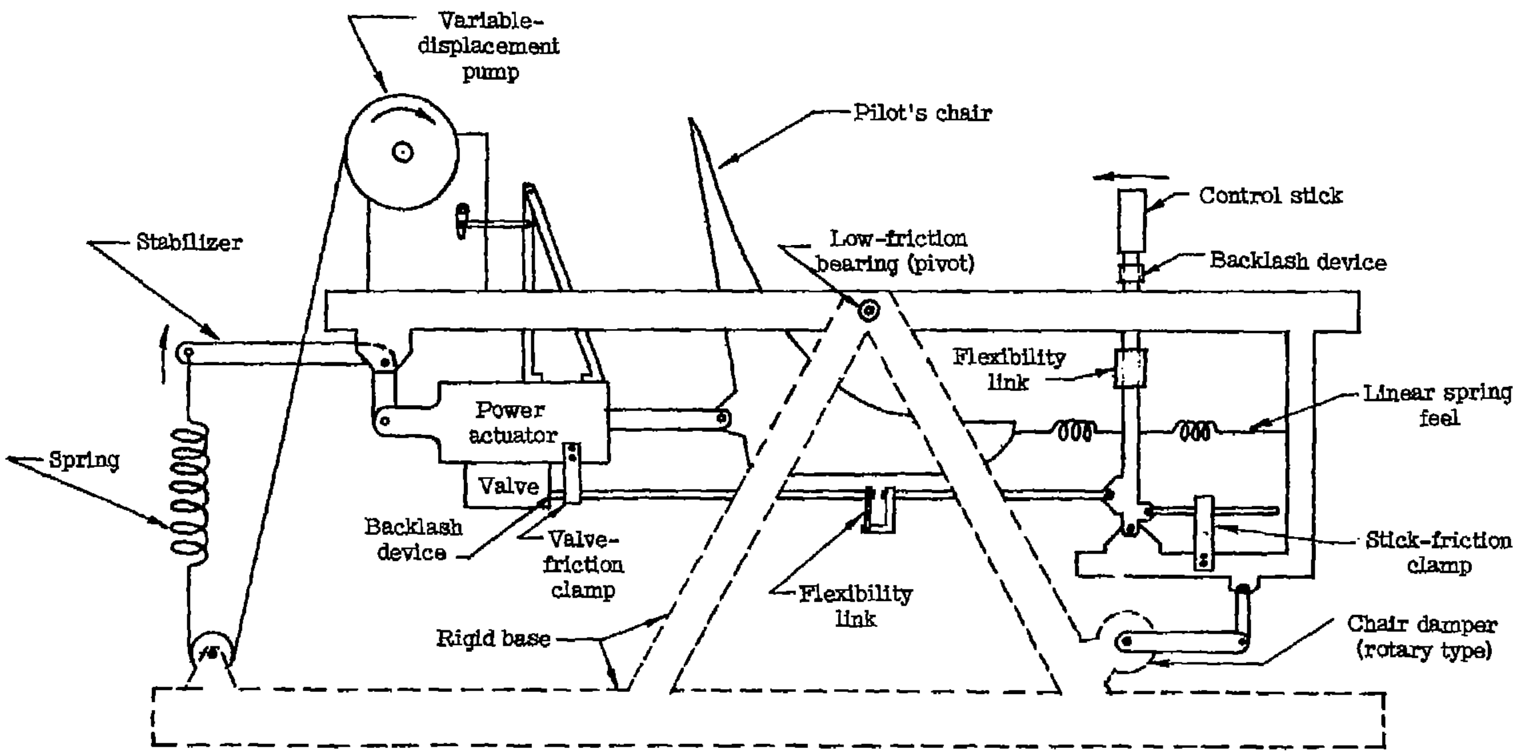


Figure 2.- Schematic drawing of simulator. Solid lines indicate movable parts. Arrows indicate direction of motion of stick, stabilizer, and pump drum associated with pullup.

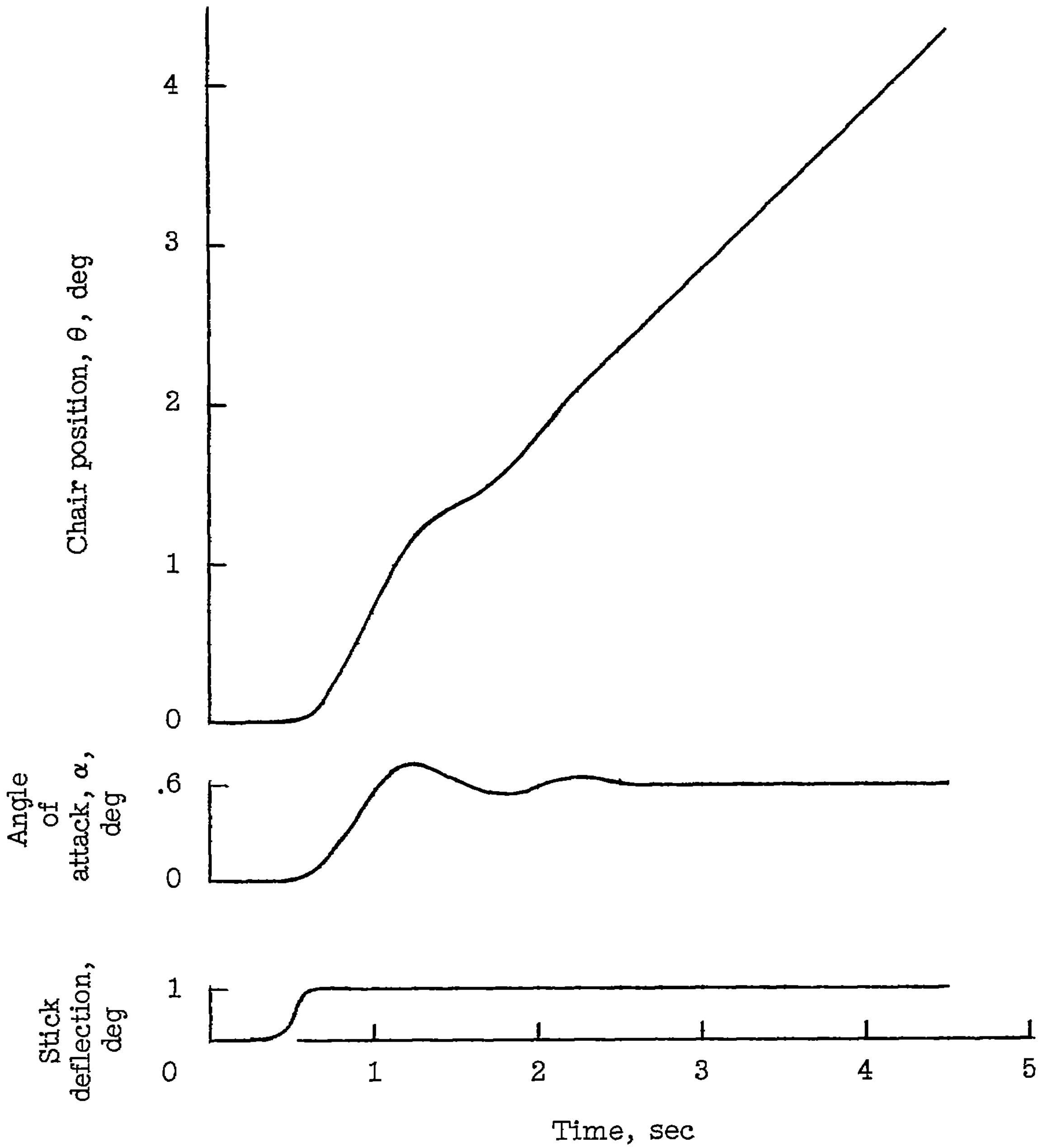


Figure 3.- Time history showing response of chair to step stick deflection.

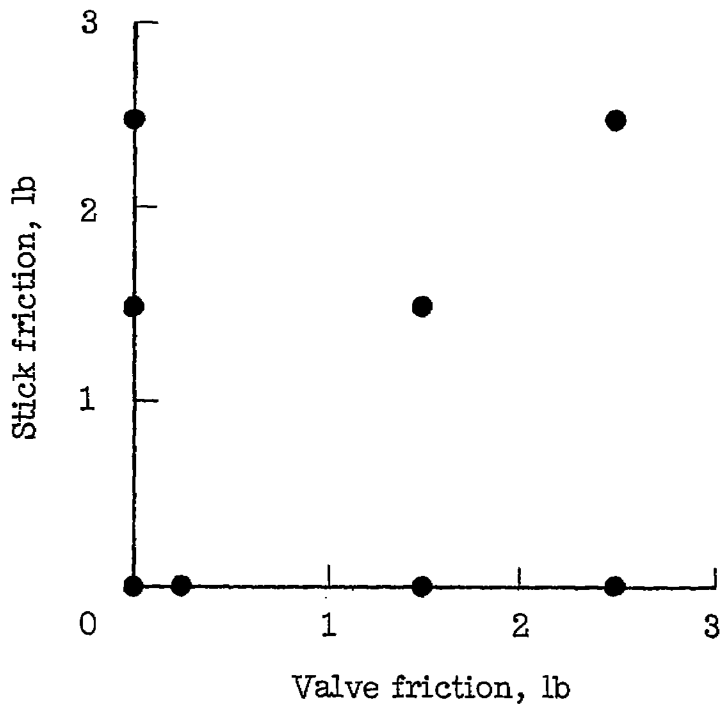
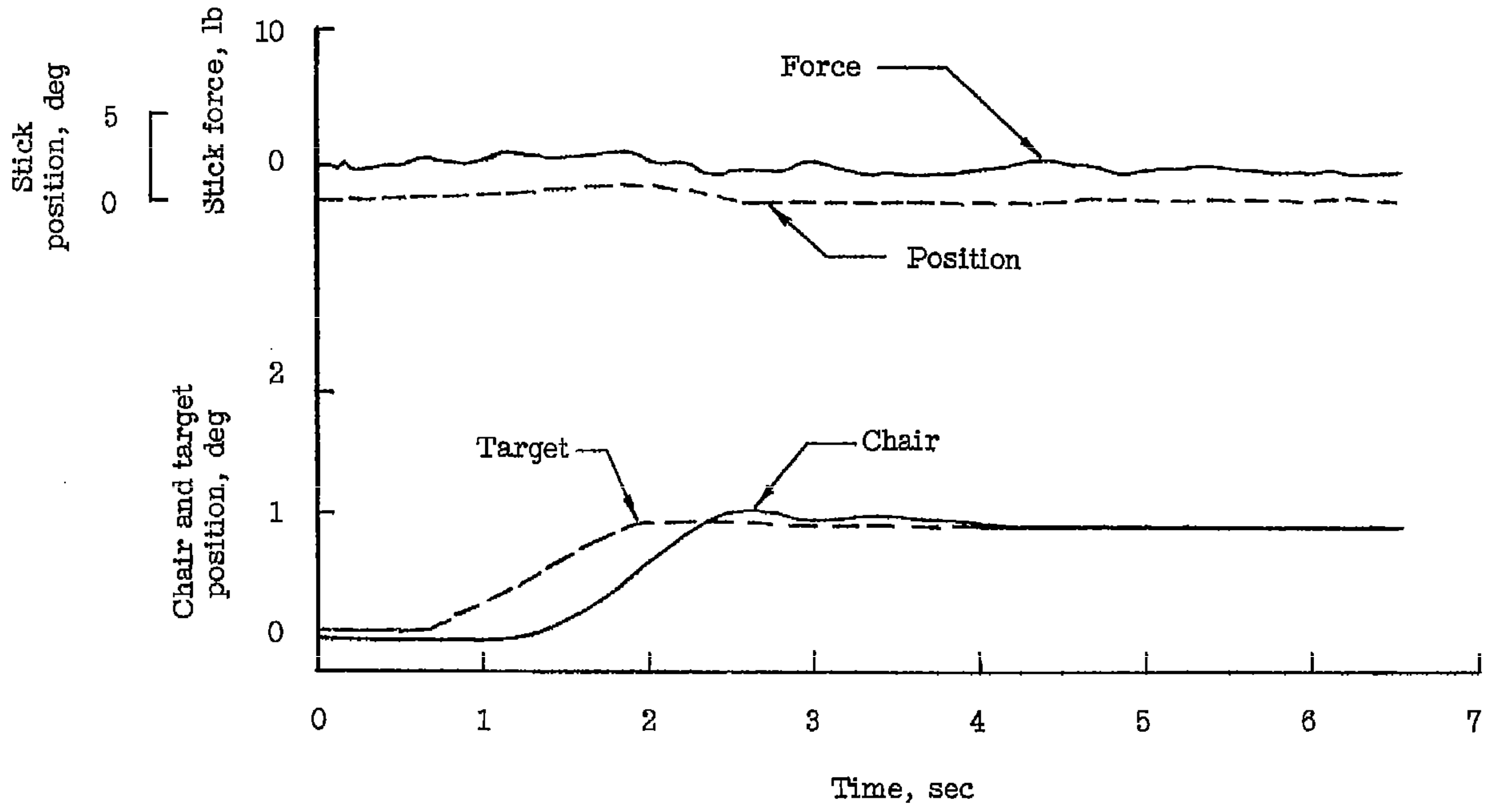
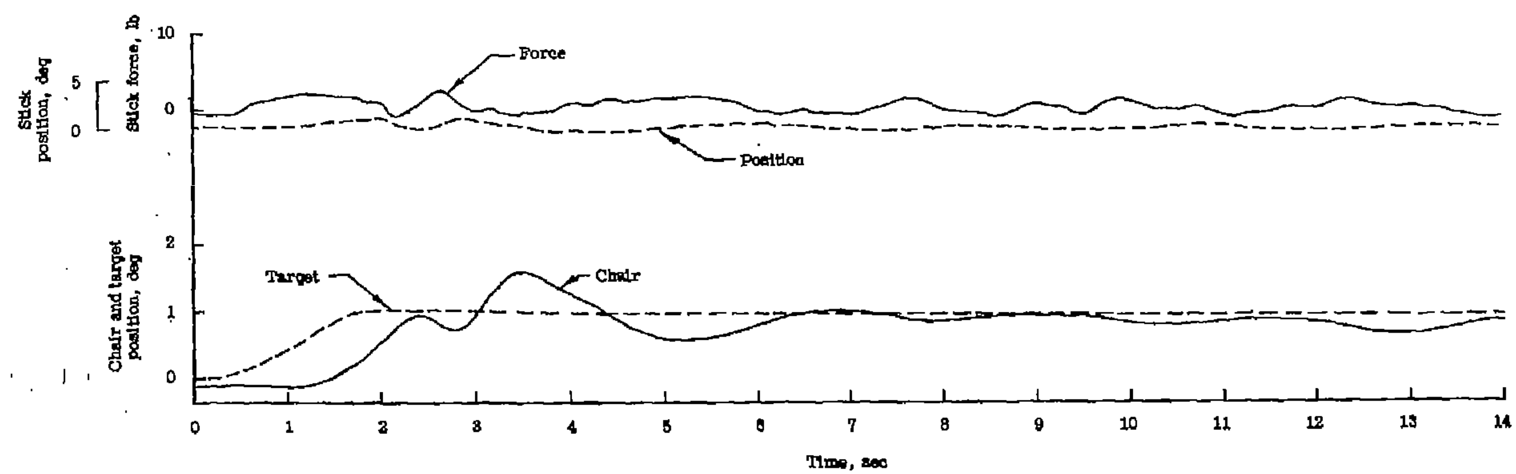


Figure 4.- Friction conditions tested.



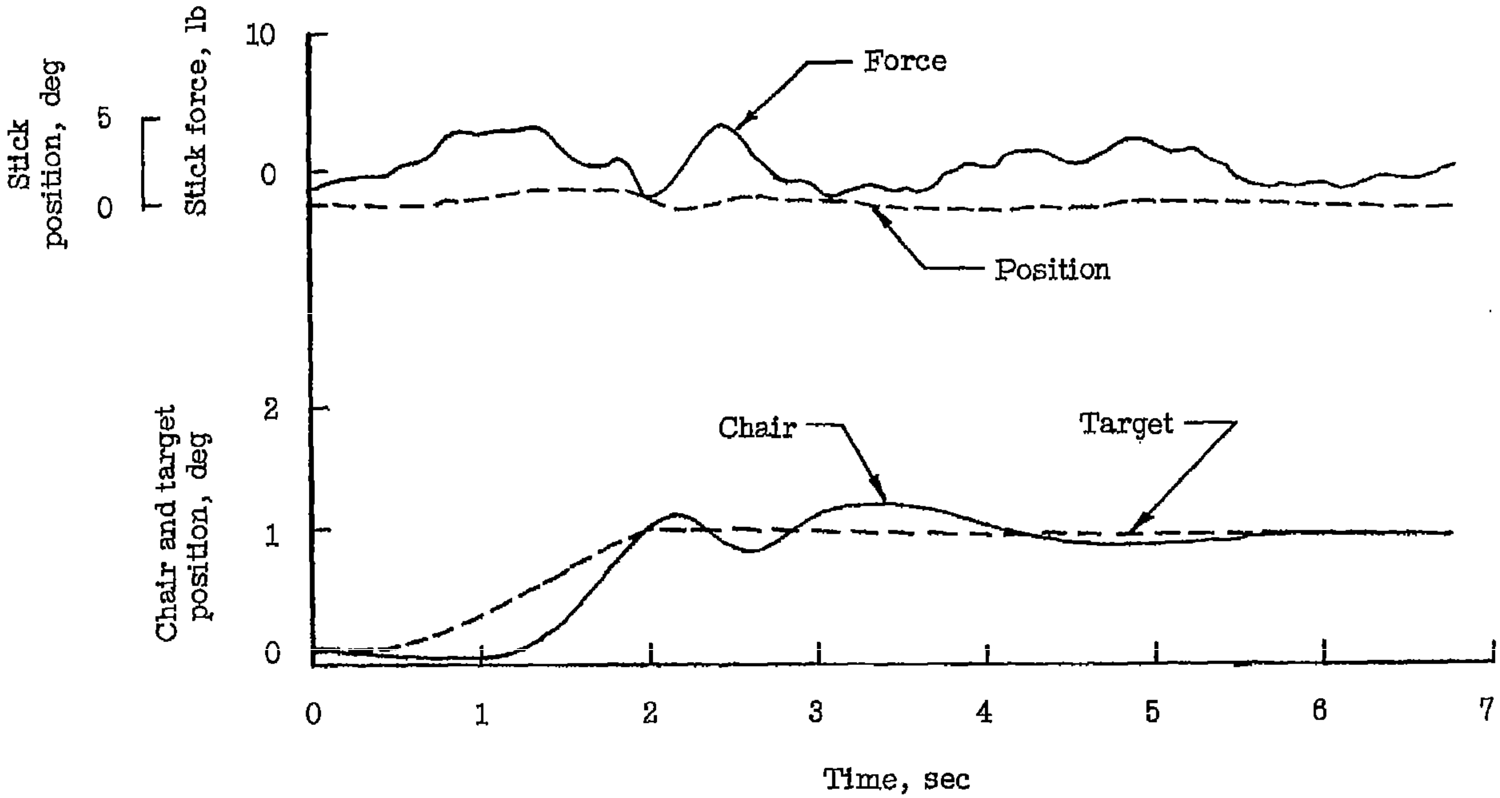
(a) No friction.

Figure 5.- Rigid control system.



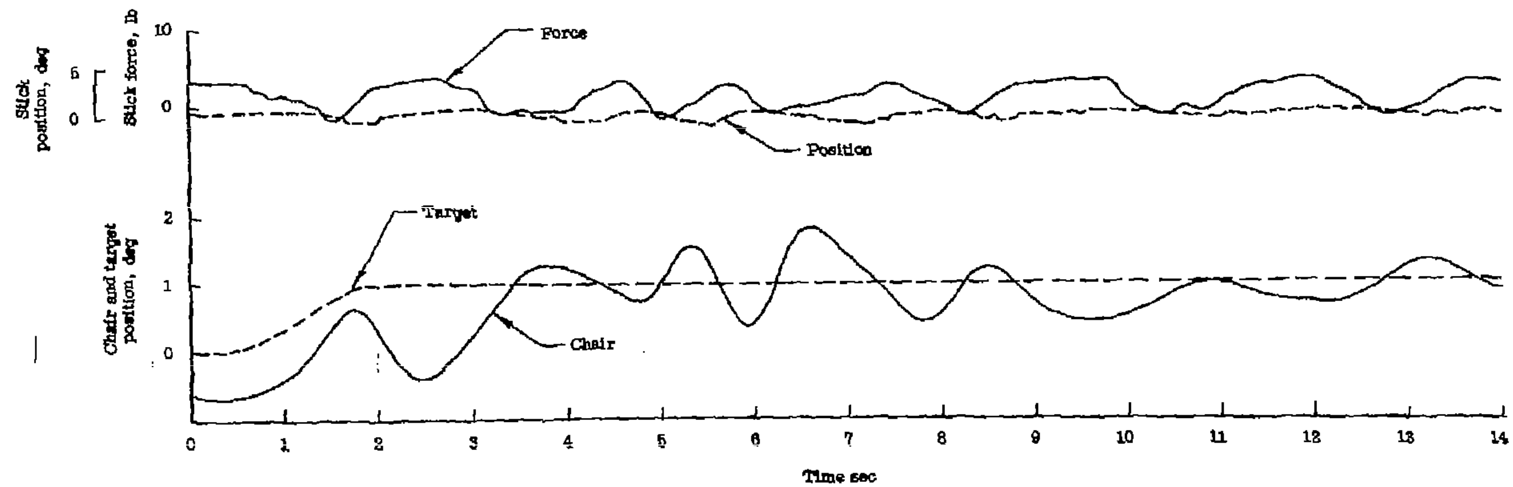
(b) $1\frac{1}{2}$ pounds valve friction.

Figure 5.- Continued.



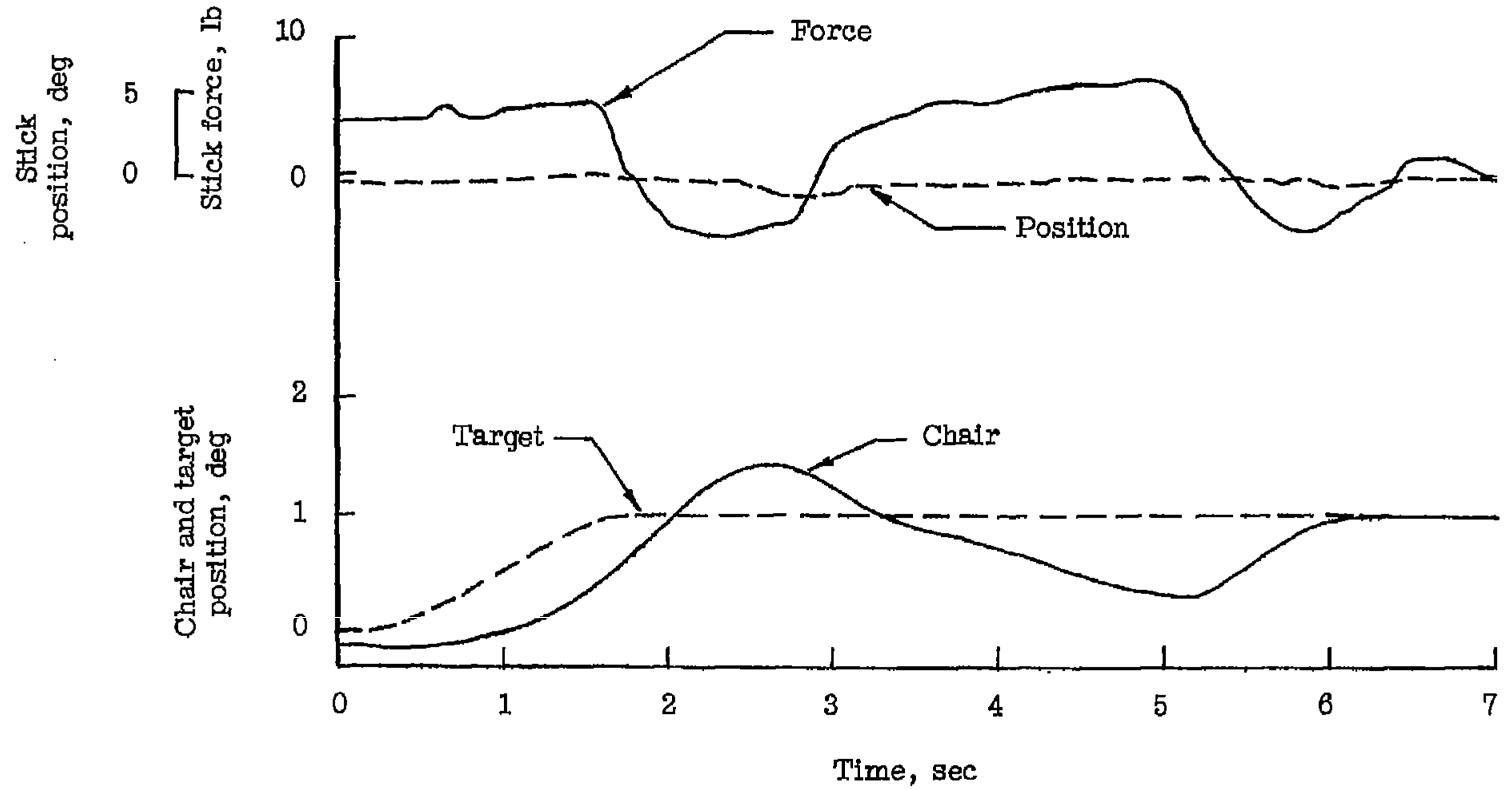
(c) $1\frac{1}{2}$ pounds valve friction and $1\frac{1}{2}$ pounds stick friction.

Figure 5.- Continued.



(d) $2\frac{1}{2}$ pounds valve friction.

Figure 5.- Continued.



(e) $2\frac{1}{2}$ pounds valve friction and $2\frac{1}{2}$ pounds stick friction.

Figure 5.- Concluded.

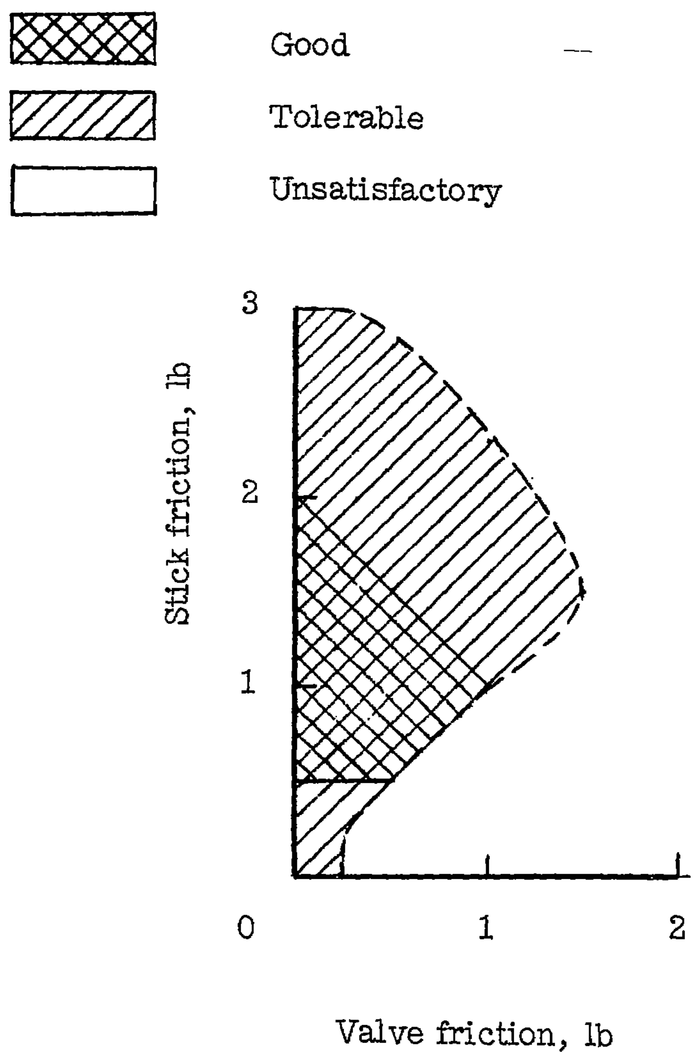
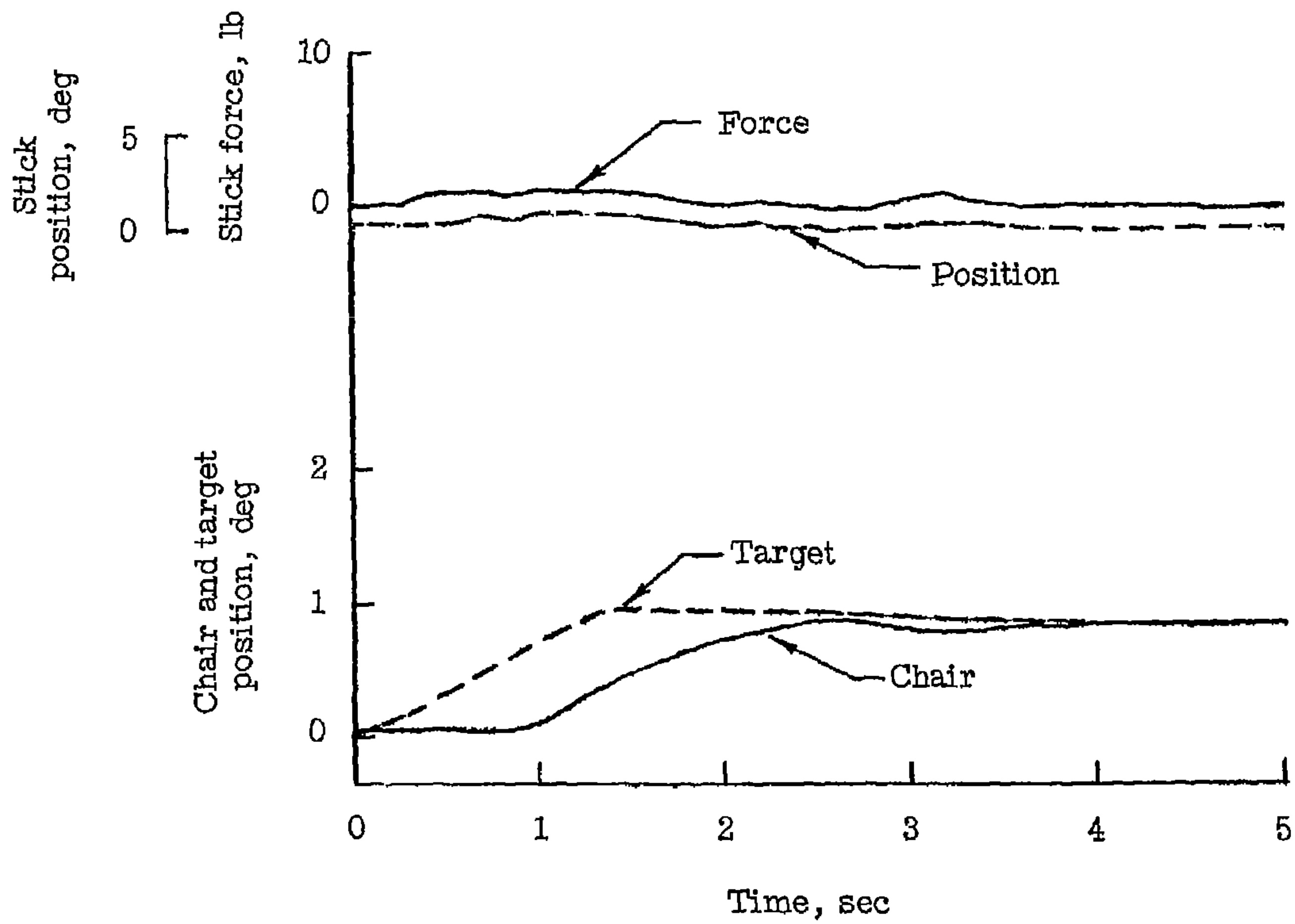
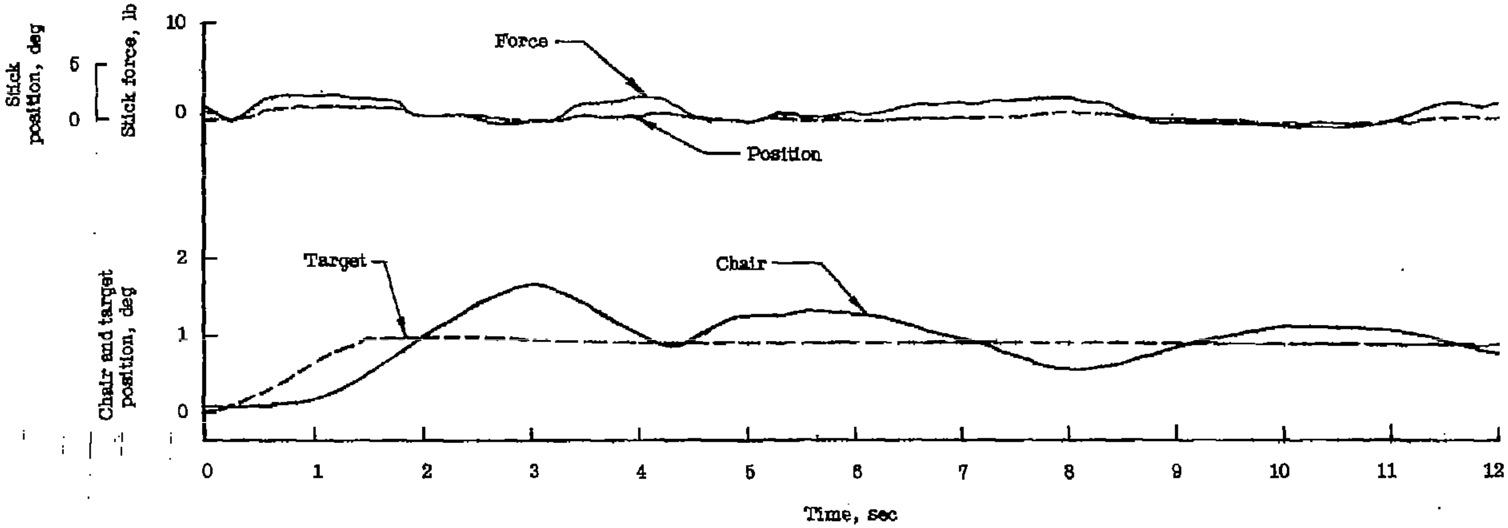


Figure 6.- Combinations of valve friction and stick friction for rigid control system.



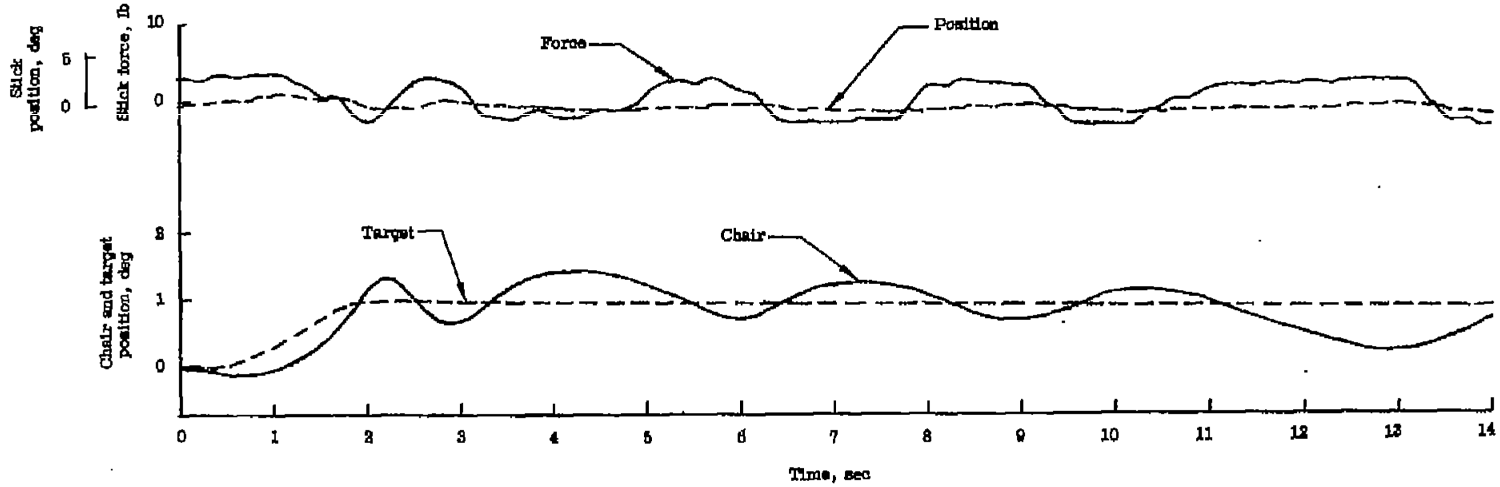
(a) No friction.

Figure 7.- Flexibility between stick friction and valve friction.



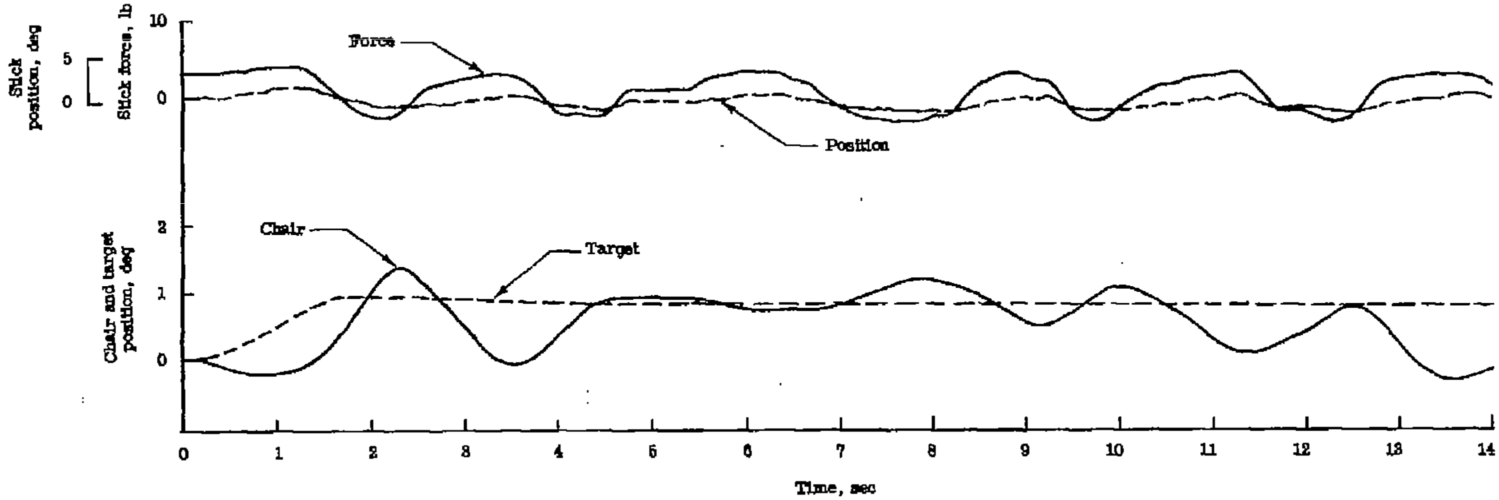
(b) $1\frac{1}{2}$ pounds valve friction.

Figure 7.- Continued.



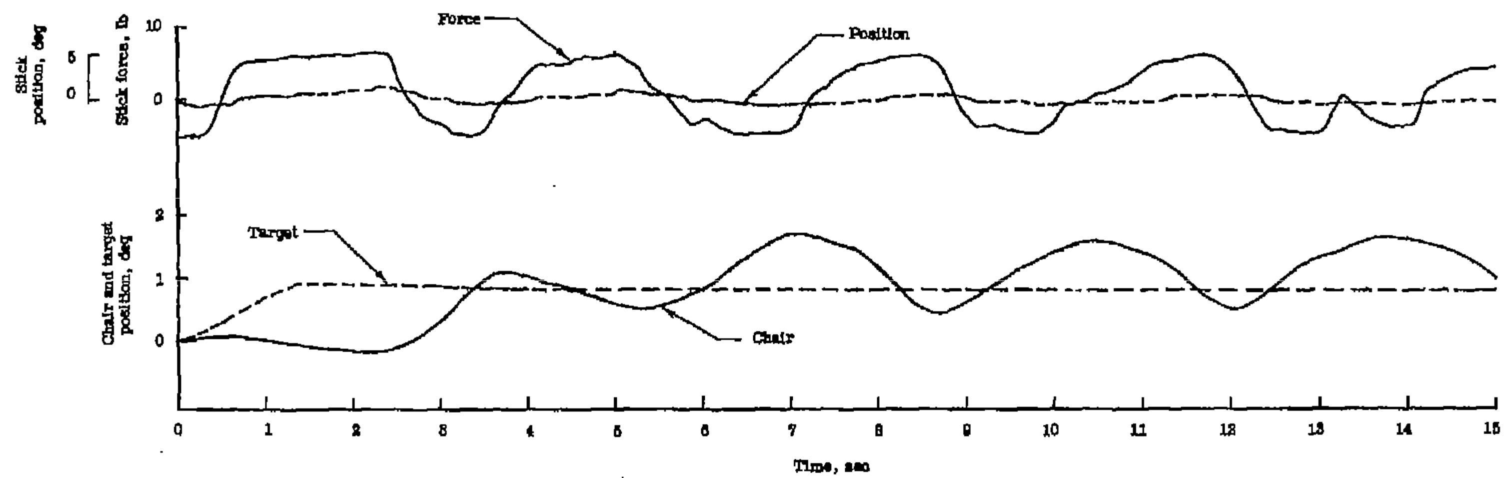
(c) $1\frac{1}{2}$ pounds valve friction and $1\frac{1}{2}$ pounds stick friction.

Figure 7.- Continued.



(d) $2\frac{1}{2}$ pounds valve friction.

Figure 7.- Continued.



(e) $2\frac{1}{2}$ pounds valve friction and $2\frac{1}{2}$ pounds stick friction.

Figure 7.- Concluded.

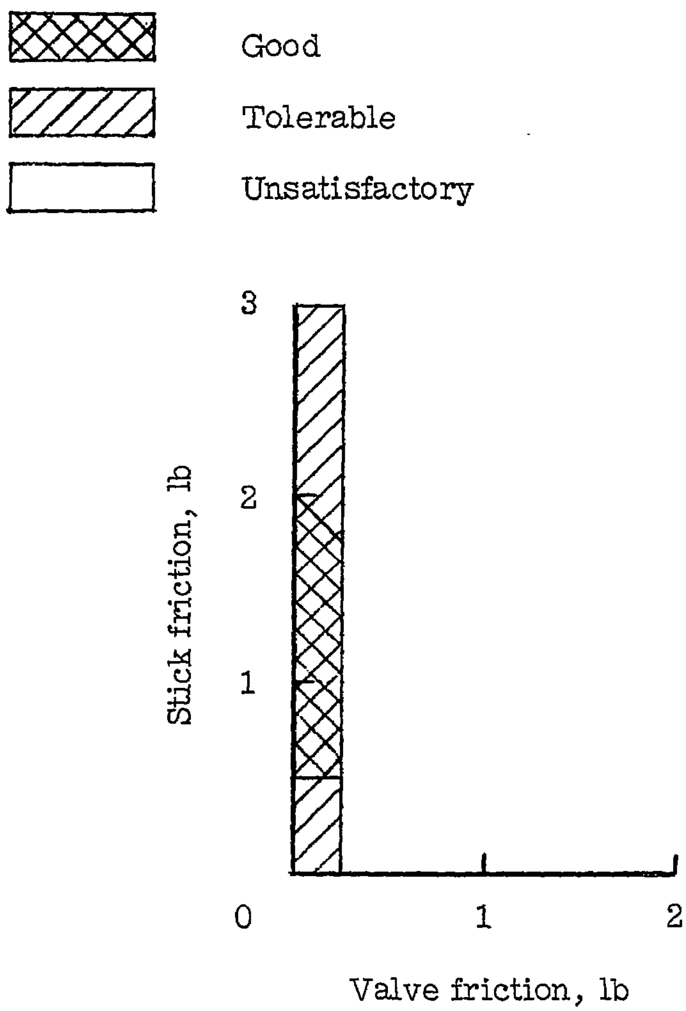
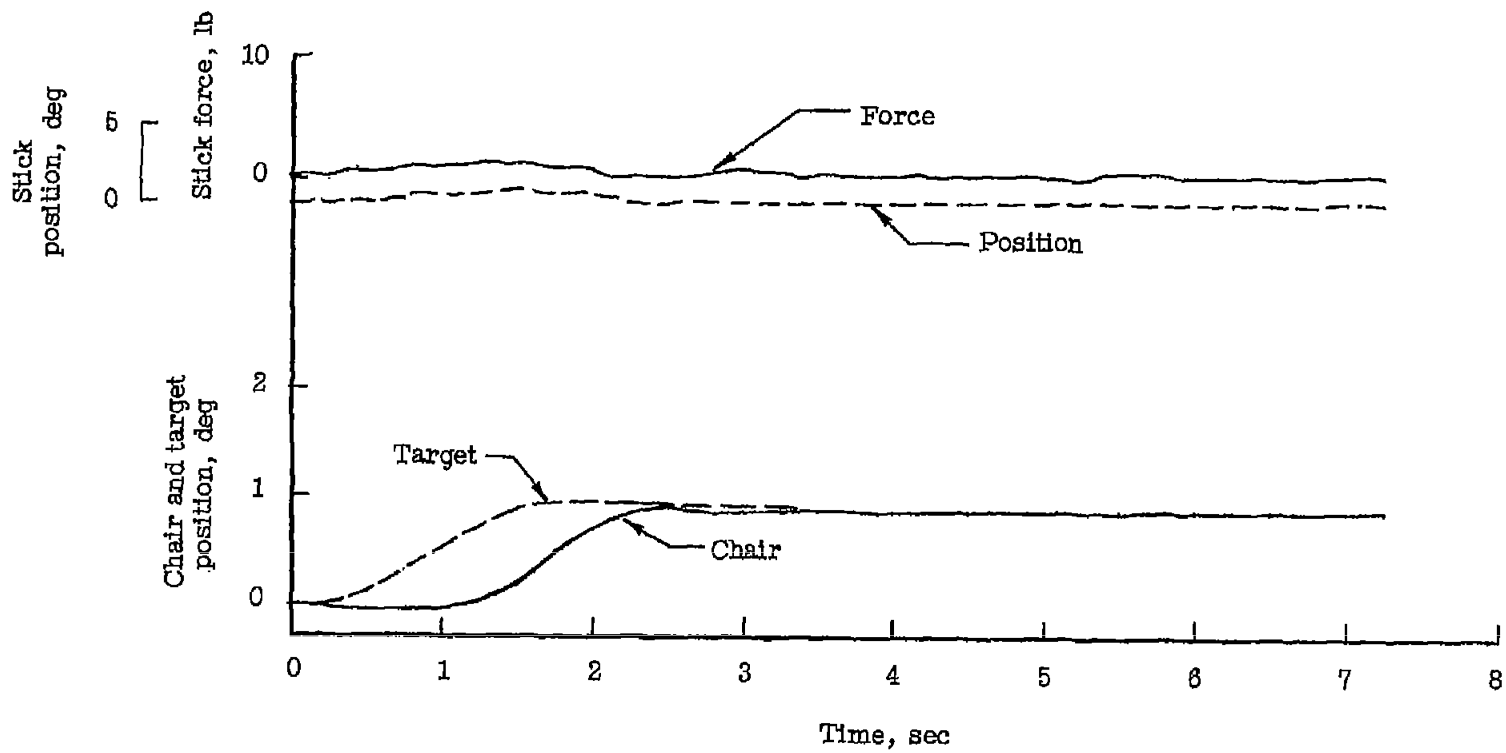
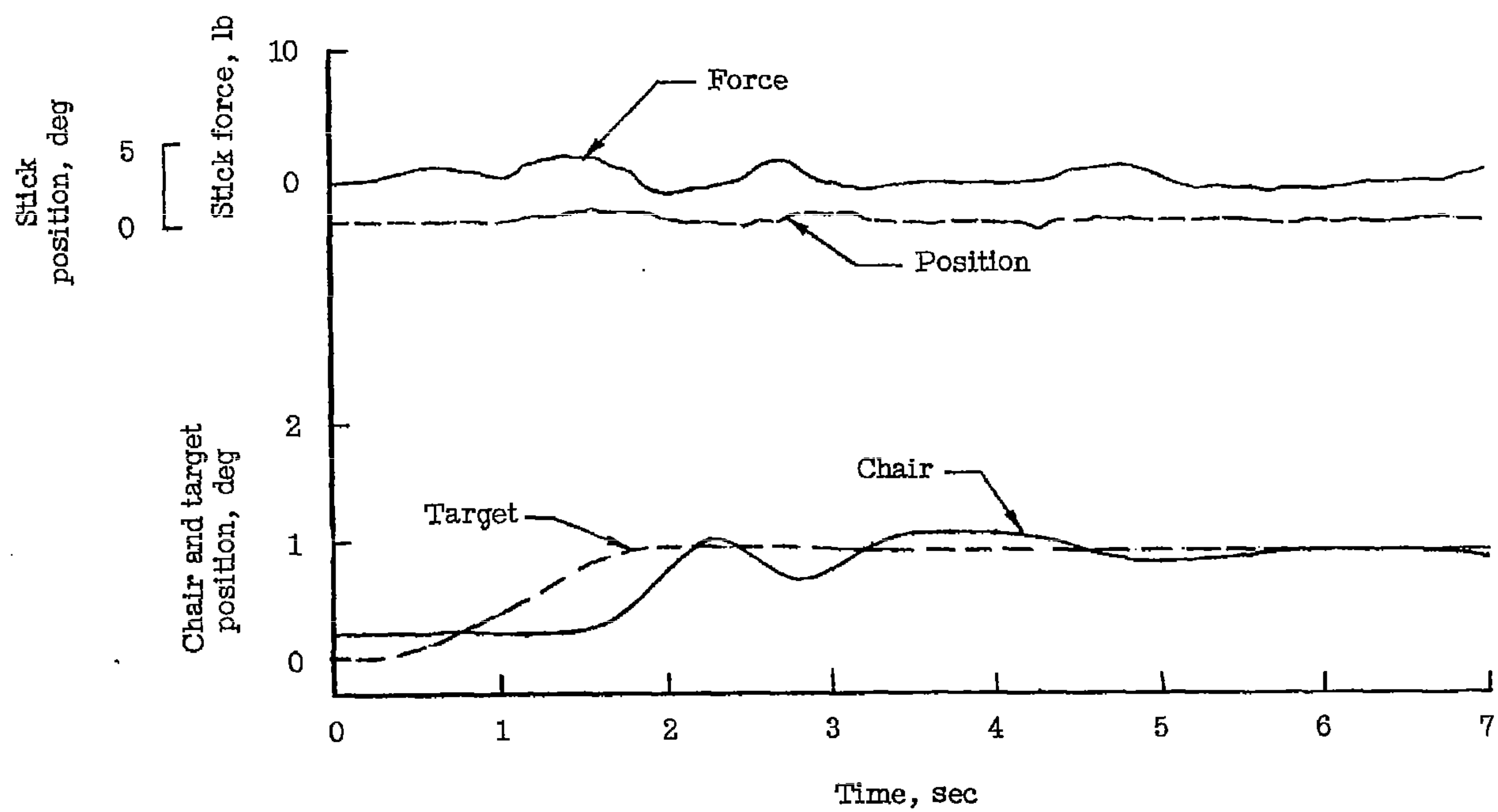


Figure 8.- Combinations of valve friction and stick friction with flexibility between the stick and the valve.



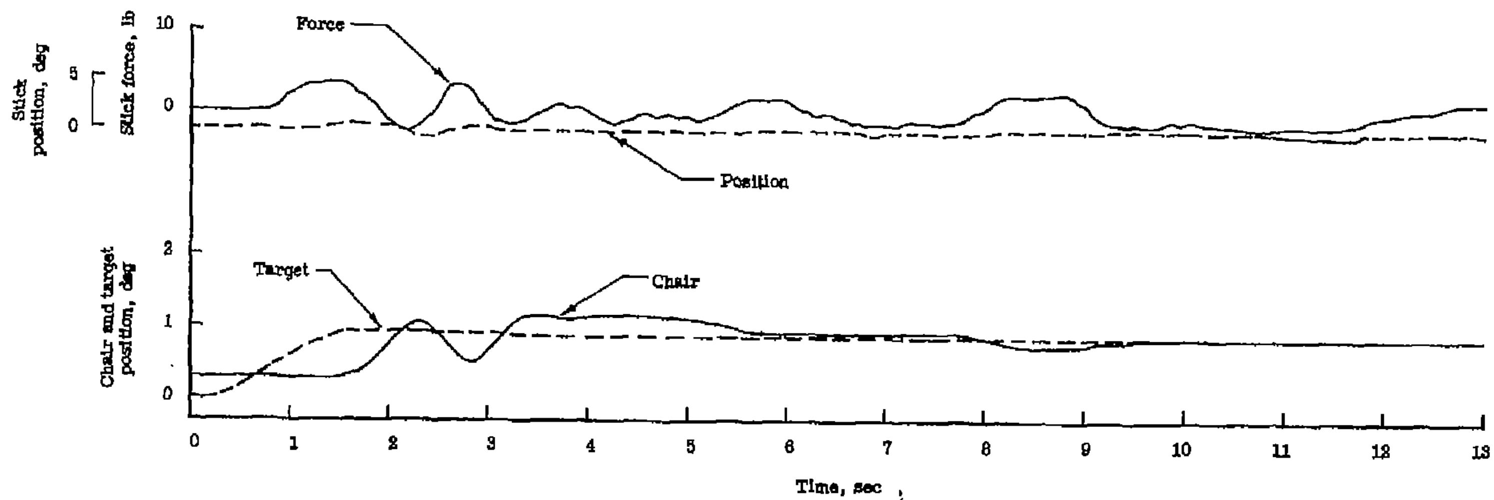
(a) No friction.

Figure 9.- Flexibility between the pilot and the stick friction.



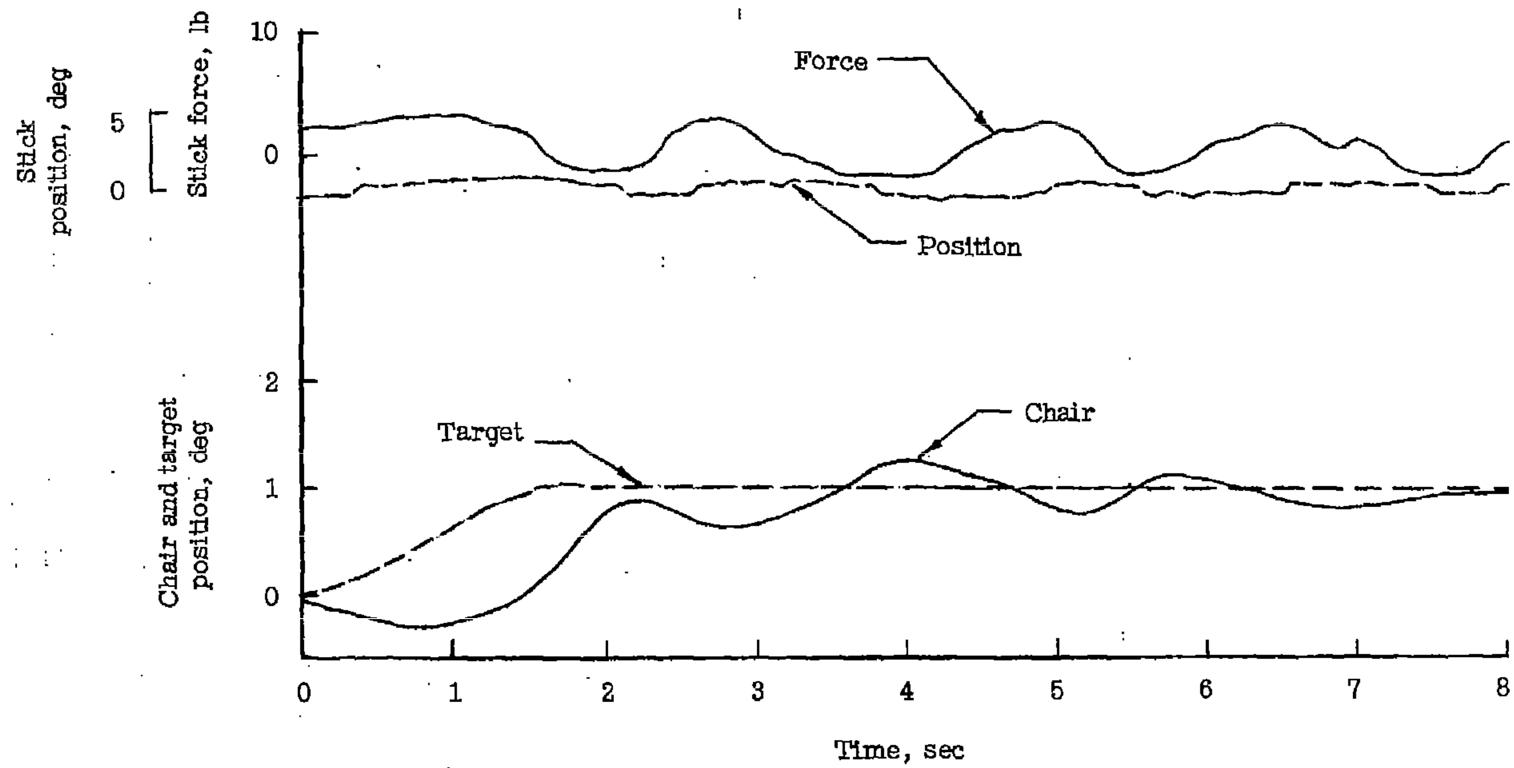
(b) $1\frac{1}{2}$ pounds valve friction.

Figure 9.- Continued.



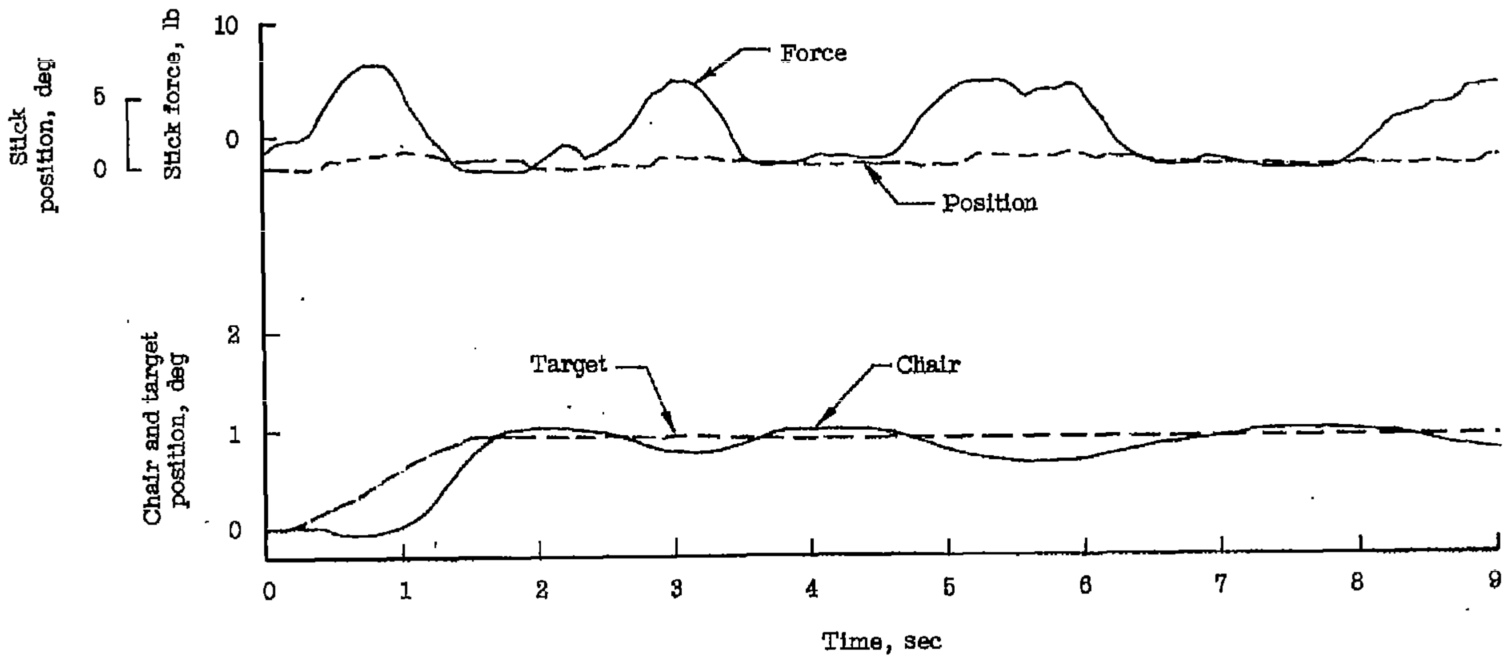
(c) $1\frac{1}{2}$ pounds valve friction and $1\frac{1}{2}$ pounds stick friction.

Figure 9.- Continued.



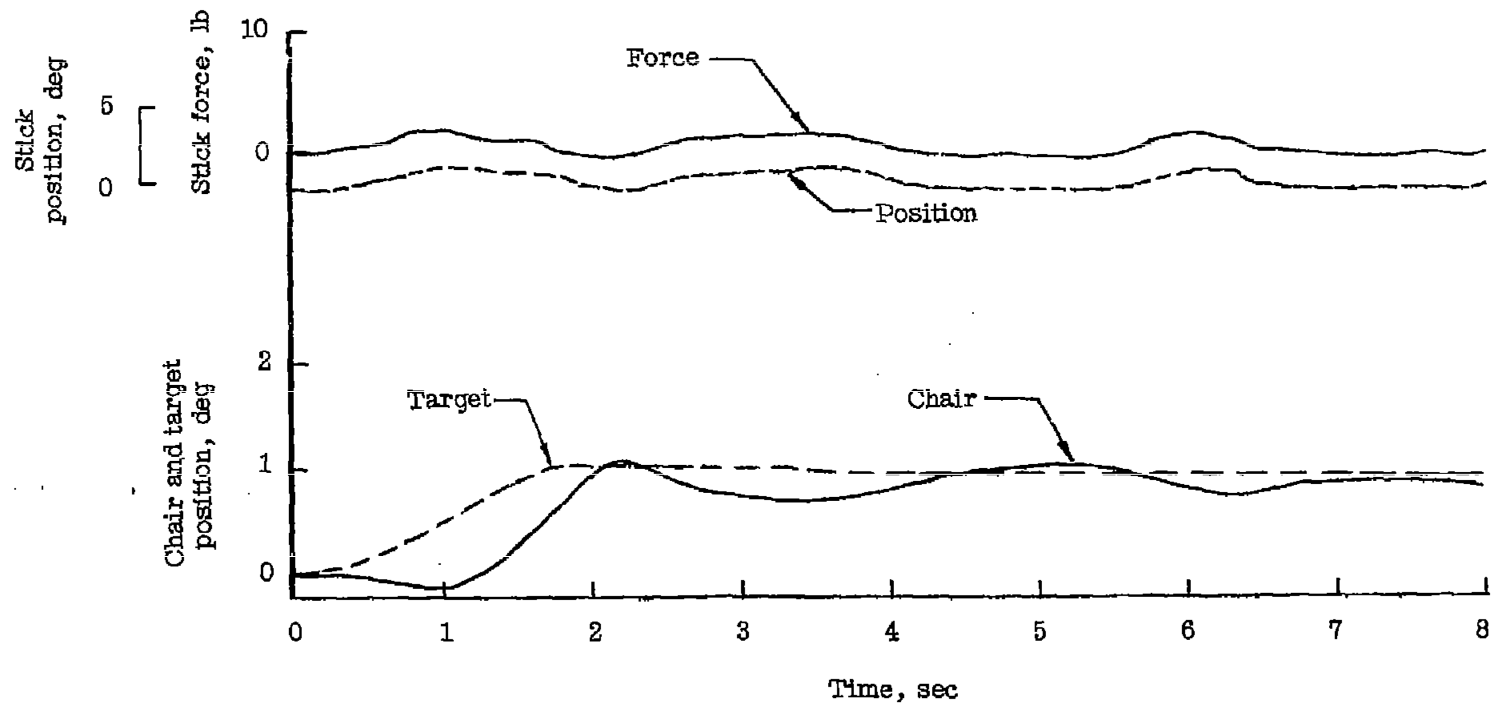
(d) $2\frac{1}{2}$ pounds valve friction.

Figure 9.- Continued.



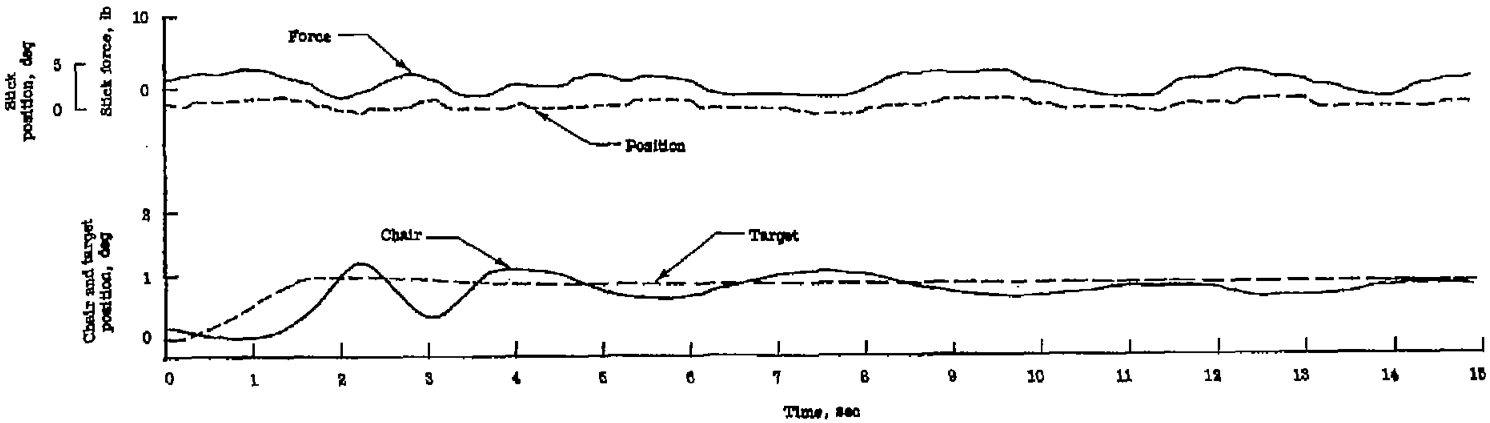
(e) $2\frac{1}{2}$ pounds valve friction and $2\frac{1}{2}$ pounds stick friction.

Figure 9.- Concluded.



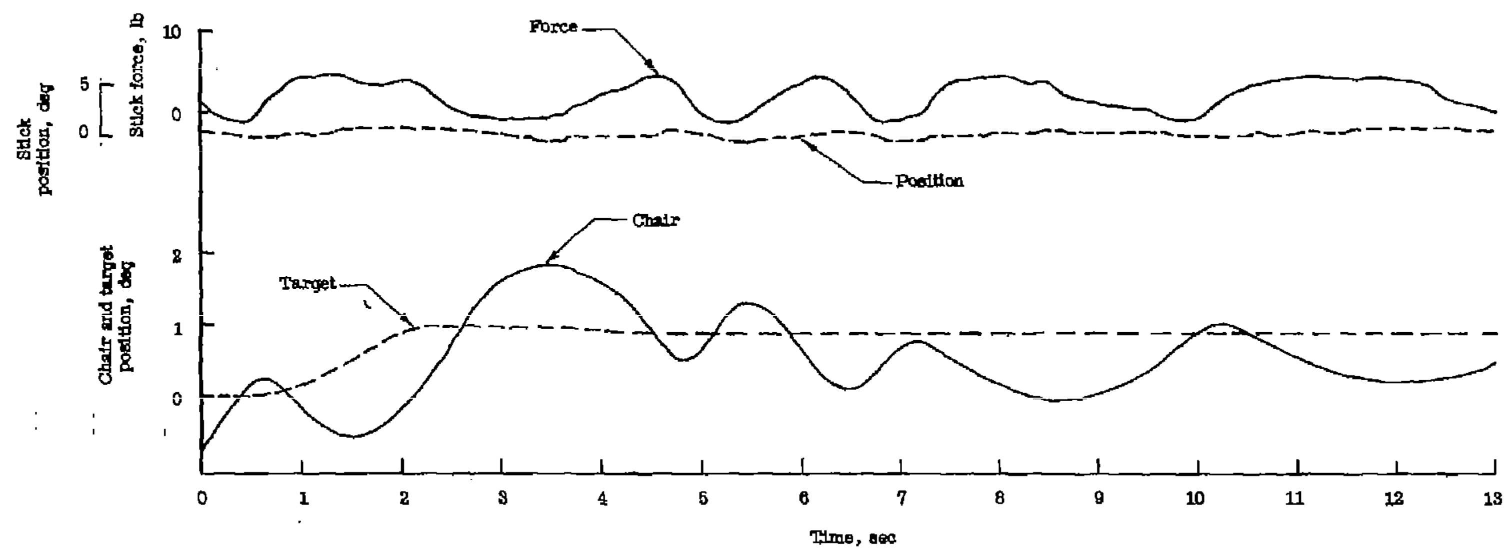
(a) No friction.

Figure 10.- Backlash between the stick and the valve.



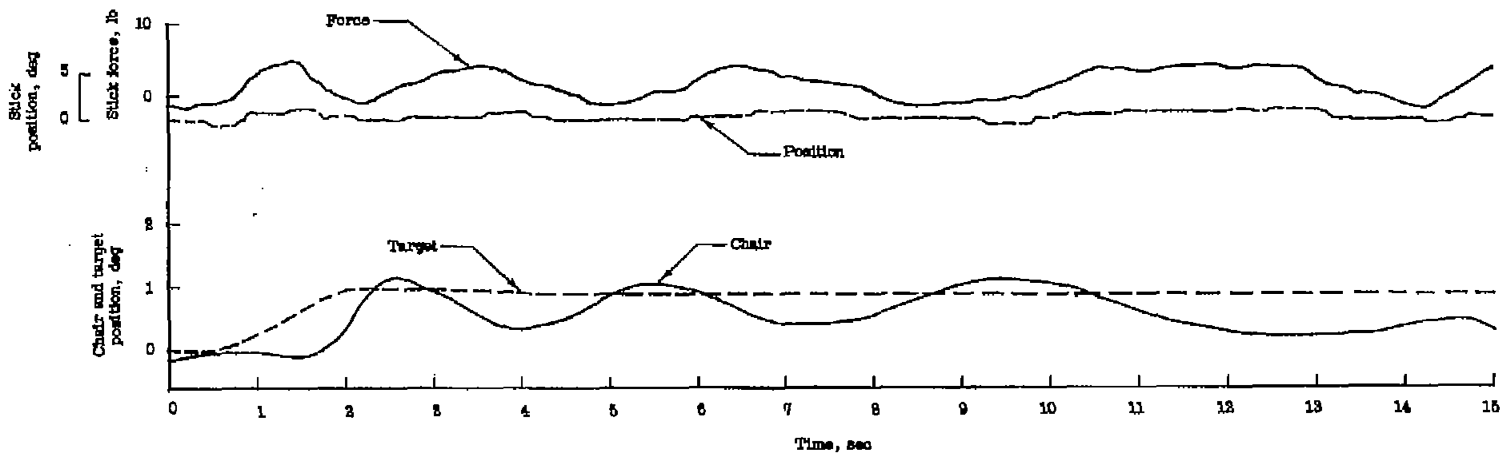
(b) $1\frac{1}{2}$ pounds valve friction.

Figure 10.- Continued.



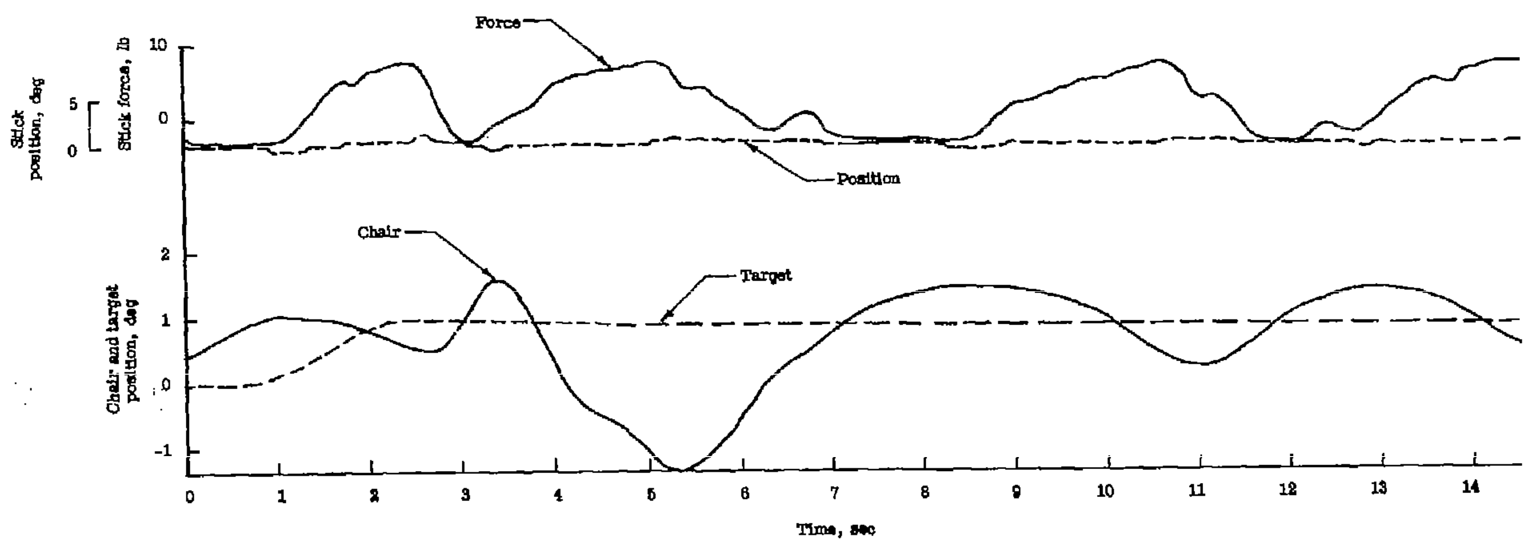
(c) $1\frac{1}{2}$ pounds valve friction and $1\frac{1}{2}$ pounds stick friction.

Figure 10.- Continued.



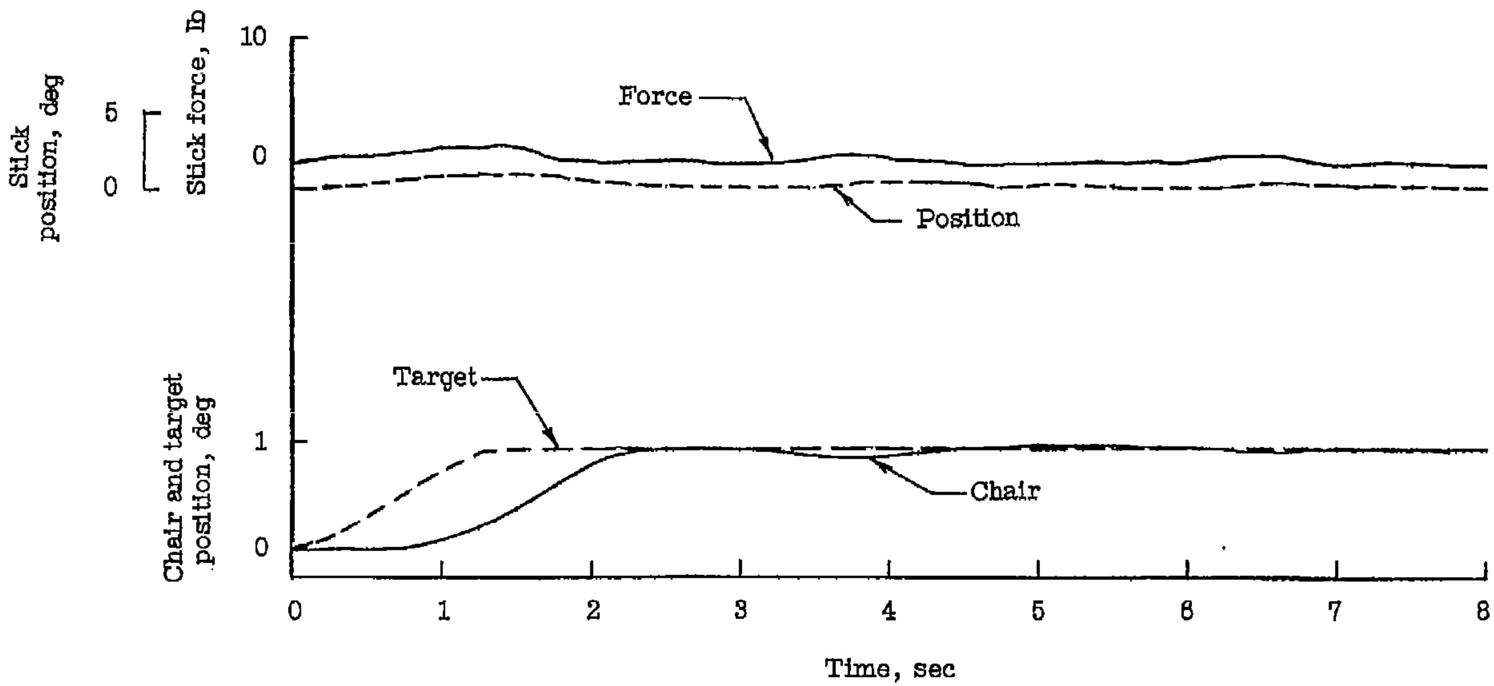
(d) $2\frac{1}{2}$ pounds valve friction.

Figure 10.- Continued.



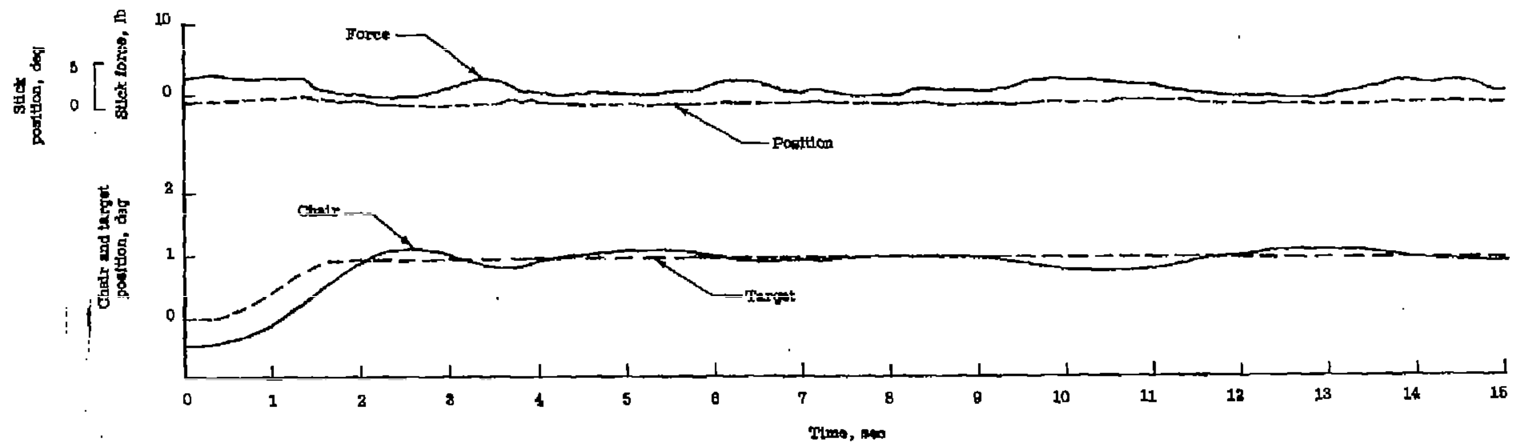
(e) $2\frac{1}{2}$ pounds valve friction and $2\frac{1}{2}$ pounds stick friction.

Figure 10.- Concluded.



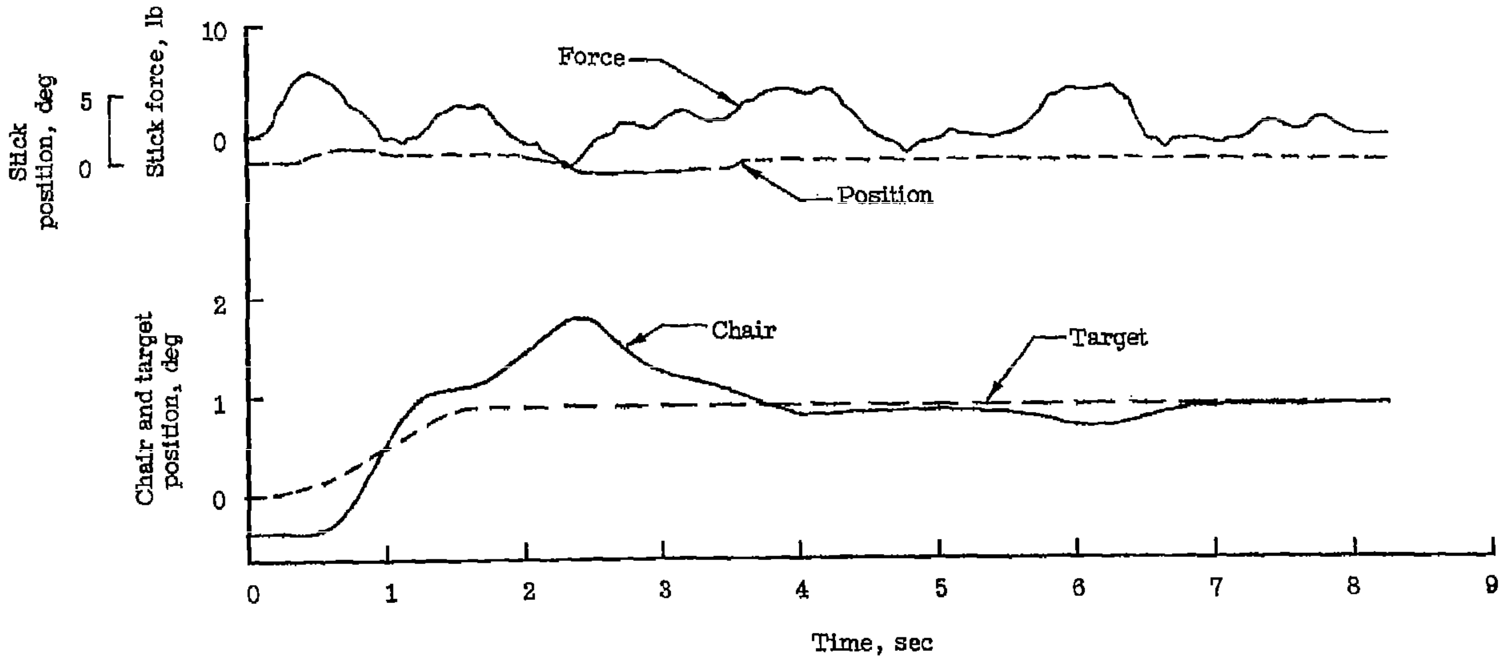
(a) No friction.

Figure 11.- Backlash between the pilot and the stick friction.



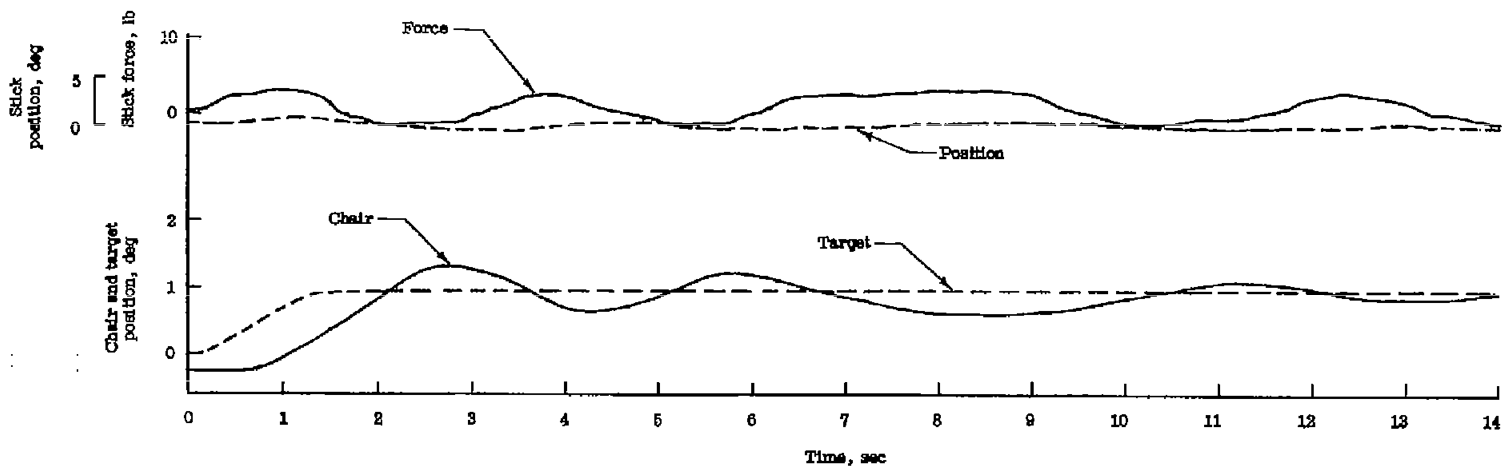
(b) $1\frac{1}{2}$ pounds valve friction.

Figure 11.- Continued.



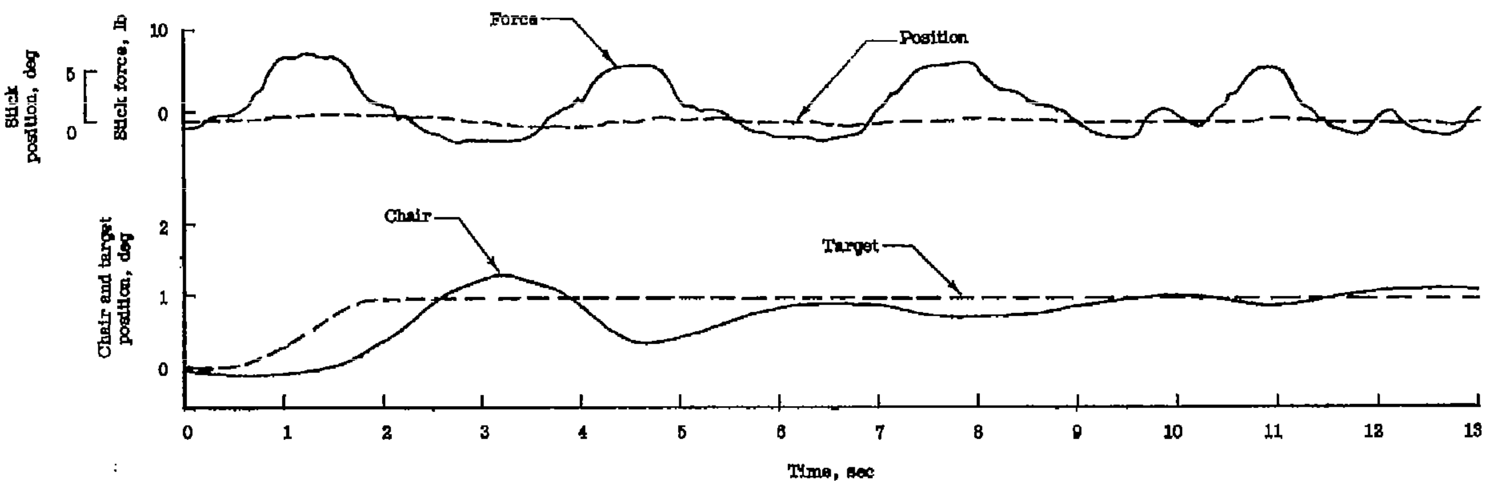
(c) $1\frac{1}{2}$ pounds valve friction and $1\frac{1}{2}$ pounds stick friction.

Figure 11.- Continued.



(d) $2\frac{1}{2}$ pounds valve friction.

Figure 11.- Continued.



(e) $2\frac{1}{2}$ pounds valve friction and $2\frac{1}{2}$ pounds stick friction.

Figure 11.- Concluded.